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CLINICAL REVIEW

Sleep and memory in healthy children and adolescents – A critical review

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S U M M A R Y

There is mounting evidence that sleep is important for learning, memory and the underlying neural plasticity. This article aims to review published studies that evaluate the association between sleep, its distinct stages and memory systems in healthy children and adolescents. Furthermore it intends to suggest directions for future research. A computerised search of the literature for relevant articles published between 1966 and March 2008 was performed using the keywords "sleep", "memory", "learn", "child", "adolescents", "adolescence" and "teenager". Fifteen studies met the inclusion criteria. Published studies focused on the impact of sleep on working memory and memory consolidation. In summary, most studies support the hypothesis that sleep facilitates working memory as well as memory consolidation in children and adolescents. There is evidence that performance in abstract and complex tasks involving higher brain functions declines more strongly after sleep deprivation than the performance in simple memory tasks. Future studies are needed to better understand the impact of a variety of variables potentially modulating the interplay between sleep and memory, such as developmental stage, socioeconomic burden, circadian factors, or the level of post-learning sensory and motor activity (interference). This line of research can provide valuable input relevant to teaching, learning and public health policy.

Introduction

Over the past years, an increasing number of scientific articles has indicated the growing interest in the interplay between sleep and memory. There is mounting evidence that sleep promotes memory and the underlying neural plasticity in animals and humans.[1–4] Some reviews cover particular sub-populations, including healthy adults[5–7] and children with sleep disorders or other disorders affecting sleep.[8–12] There are also thorough reviews on the association between sleep and academic performance[13] as well as on the impact of sleep and sleep loss on various aspects of neuropsychological functioning and behaviour in children and adolescents.[14] However, to our knowledge, a review of studies focusing on sleep and memory in healthy children and adolescents is missing so far. This paper intends to fill this gap by critically reviewing studies investigating the association between sleep and memory in healthy children and adolescents. Additionally, suggestions for the direction of future research are presented.

Memory stages and memory systems

Newly acquired memory traces (encoding) are initially unstable and require a process of strengthening (consolidation) to become resistant to interference and accessible for delayed retrieval. A growing body of data, largely derived from adult human and animal studies, suggests that sleep fosters distinct stages of memory processing, including encoding, consolidation, retrieval, or even further processing such as reconsolidation and integration into existing memory networks.[15]

In addition to the concept of encoding, current theories of working memory emphasize that even early representations are not simply passively maintained but selected and further processed before they are stored in long-term memory.[16]

Human long-term memory has been conceptualised in the frame of different classification schemes, the most popular being based on the distinction between declarative and non-declarative memory.[17] Declarative or explicit memory is viewed as the consciously accessible memories of factual information. Several

Abbreviations: PSG, Polysomnography; REM, Rapid eye movement; NREM, Non-REM; SWS, Slow wave sleep; MSLT, Multiple sleep latency test.

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subcategories of this system have been proposed, including episodic memory, i.e., memory for events in the past, and semantic memory, which refers to general knowledge and is not related to a specific event.[18] In contrast, non-declarative memory is regarded as non-conscious. The non-declarative category comprises procedural memory, such as the learning of actions, habits and motor skills, as well as other types of implicit learning.[18]

Memory and development

Throughout the lifespan, but especially during early stages of development, learning, memory and their underlying neural plasticity are a fundamental characteristic allowing living organisms to acquire novel information and to effectively hone skills in response to internal and environmental changes.[19,20] Neural refinement occurs in response to external and internal challenges. In a complex process, it seems to parallel functional and structural brain maturation occurring in the course of development, such as an increasing local concentration of specialised functions.[21] Visuospatial working memory, for instance, undergoes both quantitative changes, i.e., a refinement of local connectivity, and qualitative improvements, i.e., improved connectivity between distinct brain regions, among them the prefrontal cortex (PFC).[21] The PFC itself develops columnar modules that form cognitive fields relevant for a specific cognitive function. These become reorganised through training.[22] The impact of developmental aspects on long-term memory representations and their supposed reliance on heterogeneous neural modules remain to be further examined.

Sleep and development

Sleep is an active process of the central nervous system. It is associated with a replay and reorganisation of neuronal activity.[23] Compared to adulthood, childhood is characterised by a longer sleep duration and larger amounts of SWS and REM sleep.[10,24,25] Results from longitudinal EEG sleep studies suggest that sleep regulation undergoes a period of maturation during infancy. Specifically, EEG theta activity during NREM sleep – but not delta activity, as in adults – seems to mark the dissipation of sleep propensity during early infancy.[26] From prepuberty on, the decline of slow-wave sleep throughout adolescence may reflect developmental alterations of the brain rather than changes in sufficiently matured sleep regulatory processes.[27] Using high-density sleep EEG, a lower frontal predominance of slow wave activity has been observed in children and adolescents compared to adults,[28] possibly reflecting the late maturation of the frontal cortex.[29] Sleep seems to be particularly important during early brain development up to the age of two years when a child still spends more time asleep than awake. Even when starting school, sleep accounts for up to 50 percent of the 24-h day.[10,30] Animal studies have demonstrated that developmental sleep is critically involved in brain plasticity (for review see Dang-Vu et al.[31]). In addition, the circadian timing of sleep changes with the onset of puberty: sleep-onset[32–36] is delayed, especially around the age of 14–16 years, i.e., at the mid- to late-pubertal stage.[37] Despite cultural differences, many studies have shown that adolescents world-wide sleep significantly less than the recommended 9–10 h.[33,38–40]

Relevant psychosocial factors seem to include the waning influence of parents on bedtimes, dedicating more time to the media, to leisure and to job-related activities, and the desire for greater self-determination.[33,34,41] Intrinsic regulatory mechanisms in adolescents, i.e., circadian timing, show a later onset of melatonin increase, resulting in a phase-delay preference during puberty.[34,42]

Considering the significant role brain plasticity processes and memory formation play in individual development and social functioning, it is important to investigate the association between sleep and memory in healthy children and adolescents.

Methods

A computerised search of the medical and psychological literature for articles published between 1966 and March 2008 was performed using the databases Medline and PsycINFO. The following terms (keywords) were used: "sleep", "memory", "learn", "child", "adolescents", "adolescence" and "teenager". Search results were limited to original articles and short communications in German and English. The bibliographies of the selected articles were searched manually for any articles not captured by the computerised search. Case reports, review articles, abstracts, dissertations, and letters were excluded. Only studies with participants up to 18 years of age were selected. Studies not investigating memory but other domains, such as academic performance, attention, mood, quality of life, or behaviour were not included. All in all, 15 studies reported in 14 published articles were analysed for this review.

Sleep, memory encoding and working memory

In comparison to a plethora of studies on adults,[15] relatively few studies have investigated the impact of sleep on memory encoding and working memory in children and adolescents. Most studies support the notion that sleep is critically involved in memory encoding and working memory. Interestingly, these studies hint towards a more complex picture showing that a number of parameters including sleep and memory task characteristics as well as developmental and social aspects critically modulate the interplay between sleep and memory.

Sadeh and colleagues[43] examined the association between sleep – monitored by actigraphy for 5 consecutive nights – and neurobehavioral functioning, including the encoding of declarative memory content (serial digit learning test), in school-age children (7.2–12.7 years) (Table 1). "Good" and "Poor" sleepers were identified. "Poor" sleepers showed more fragmented sleep as defined by more than three awakenings lasting 5 min or longer or reduced sleep efficiency (below 90 percent). Overall, good sleepers showed significantly better results learning digits than poor sleepers. Interestingly, in a within-subject repeated measurement design, this difference only showed up in a morning but not in a noon test session. The authors postulated that the findings were in line with the concept of sleep inertia – the decrease in performance after awakening from sleep that lasts up to several hours.[48] The results are also in line with theories of general cognitive performance emphasising the contribution of both homeostatic (prior sleep) and chronobiological (time of day) factors on performance.

Steenari et al.[44] studied the association of actigraphically monitored sleep with the performance of auditory and visual working memory (n-back task) in children aged 6–13 years. Longer sleep latency and lower sleep efficiency were associated with poorer auditory and visual working memory for all memory load levels. In contrast, shorter sleep duration was associated with lower working memory performance at the highest load level only (Table 1). The authors concluded that sleep quality rather than sleep duration appeared to be strongly associated with working memory performance.

Buckhalt et al.[46] examined race and socioeconomic status (SES) as potential moderators of sleep and cognitive functioning in children (Table 1). All participants showed similar working memory performance ('numbers reversed' derived from the

Woodstock-Johnson III test battery) when actigraphically monitored sleep was optimal. However, when sleep was disrupted (reduced sleep efficiency or elevated number of epochs with activity), children from higher SES families performed better than children from lower SES families. Furthermore, under conditions of disrupted sleep, African American children showed poorer performance. The authors pointed out that an increased number of potentially interrelated stressors, including low SES, African American background and poor sleep, might worsen cognitive performance, including working memory.

The consequences of insufficient sleep on daytime functioning were investigated in a self-report study by Oginska and Pokorski[45] (Table 1). 18.3% of adolescents reported having problems with memory ''often'' or ''almost always'', compared to 22.6% in university students and 16.7% in young adult employees. Long sleepers reported more fatigue symptoms as well as affective and cognitive problems. The association of fatigue and mood with sleep need and sleep index (ratio of actual sleep length to sleep need) were more pronounced in younger subjects. Unfortunately, detailed results for memory problems were not reported and the design of the study did not allow differentiation between different stages or types of memory. Another limitation of the study was the lack of objective assessments of sleep and distinct domains of emotion and cognition.

A number of studies assessed the effects of restricted sleep on memory. Carskadon and co-workers[49] investigated the impact of a single night of restricted sleep (4 h) on 11–13 year old children. They found no significant effects on declarative memory (short-term recall of words) and other tasks of cognition and attention (Table 2). Yet in another study by the same group[52] that assessed the effects of one night of total sleep deprivation on young adolescents (12–15 years), the number of correctly recalled words on the Williams Word Memory Test was significantly reduced under conditions of total sleep deprivation (Table 3). The authors concluded from this that children appear to tolerate a single night of sleep restriction relatively well and that relevant differences might only emerge after prolonged periods of restricted sleep or total sleep deprivation.

Randazzo et al.[50] provided further evidence that children seem to be able to partially compensate for short periods of sleep restriction. The authors examined cognitive functioning after a single night of restricted sleep (5 h in bed) in children aged 10–14 years. Impairment of higher cognitive functioning, such as verbal creativity, were found, whereas other functions, such as declarative visual and verbal learning, were not significantly affected (Table 2). Verbal learning (subscale of the Wide Range Assessment of Memory and Learning Test) was even improved after sleep restriction. Yet, this difference was presumably due to poor performance of the control group and not due to the intervention. The authors suggested that the routine nature of the chosen memory tasks with low cognitive load might be relatively resistant to short periods of sleep restriction, and that compensation mechanisms, such as increased motivation, could contribute to overcoming potential impairments after sleep restriction.

Sadeh and co-workers[51] further investigated the effects of prolonged modest sleep restriction or extension in children. After two nights with a regular sleep duration, 9–12 year old children were asked to extend or restrict their sleep time by 1 h for three consecutive nights (Table 2). Children who extended their sleep significantly improved their performance on the digit forward memory task from baseline to post-intervention testing compared to the sleep-restriction and no-change group.

Together these studies provide evidence that sleep is critically involved in memory encoding and working memory in children and adolescents. The studies also indicate that children and adolescents are able to compensate for brief periods of sleep restriction with impairments only emerging after prolonged sleep restriction or total sleep deprivation. Significant questions remain regarding the extent of sleep restriction that can be tolerated, the impact of sleep alterations on distinct types of memories, and the modulation by other variables, such as socioeconomic burden and developmental aspects.

Sleep and memory consolidation

Other studies have begun to translate the work on sleep and memory consolidation mostly done in animals and healthy adults[58] into research on children and adolescents. Most of the studies support a role for sleep in memory consolidation, although significant differences to adults might exist, e.g., limited or reversed effects of sleep on non-declarative memory consolidation during earlier stages of development.

Dworak et al.[47] investigated the impact of excessive television and computer game consumption in the evening on polysomnographically monitored sleep and overnight consolidation of declarative memory (Visual and Verbal Learning Task, VVM) in 12–14 year old boys (Table 1). Playing computer games was associated with prolonged sleep latency, increased stage 2 sleep and reduced slow wave sleep and significantly impaired verbal memory consolidation. Visual memory was not affected. Television consumption was related to decreased sleep efficiency, but no alterations of sleep architecture were found. The findings partially support the view that excessive media consumption negatively impacts sleep, learning and memory in children. However, the design of the study did not allow any differentiation between post-learning effects of disrupted sleep, such as reduced slow wave sleep, and effects of increased levels of interference (elevated sensory input and emotional processing) on memory consolidation.

In a well-designed study, Gais et al.[53] showed that declarative memory consolidation (24-pair English–German vocabulary lists) in young males (mean age 17.4 years) benefited from sleeping within a few hours after learning compared to equal periods of wakefulness. Importantly, using retention intervals of 24 h and 36 h with both morning and evening learning (resulting in four experimental conditions: morning-to-evening, evening-to-morning, evening-to-evening, and morning-to-morning), the authors were able to show that enhanced declarative recall was related to periods of sleep but not to time-of-the-day effects. The authors state that their design allowed for keeping amounts of waking-associated interference after encoding constant. Nonetheless, they issue a caveat: memories might become consolidated most effectively during a limited period after encoding that is free of interference. Therefore the authors might not have observed enhanced consolidation due to sleep-specific brain activity patterns but effects of reduced sensory input within a critical window after encoding. Since the authors assessed sleep only in the form of self reports, no objective data on sleep continuity, sleep architecture, or other EEG sleep characteristics were available. In an additional experiment, the authors investigated whether the beneficial effect of evening learning found in the first experiment could be attributed to sleep following learning or whether it was related to the time of day. For this purpose, subjects learned a list of associated word pairs at 8 pm before either a night of sleep or a night of sleep deprivation. For both groups, retesting followed 48 h after initial learning. The sleep group recalled a greater number of word pairs than the wake group which supports the finding, that sleep and not the time of day benefits learning. Conversely, one night of total sleep deprivation impairs the formation of novel declarative memories.

Backhaus et al.[56] provide further support for the notion that declarative memory consolidation (word-pair learning) in children (9–12 years) is enhanced after periods of night-time sleep

Table 1
Epidemiological studies and clinical trials without sleep deprivation.

Author	Sample	Memory type	Methods, measurements	Experimental conditions	Results
Sadeh et al.[43]	$n = 135$ 69 m, 66 f 7.2–12.7 yrs split into 3 groups: $n = 48$ 2nd grade $n = 36$ 4th grade $n = 51$ 6th grade	Visual memory, working memory	Actigraphy, Child Behaviour Check List (parental reports), teachers' report form, Neurobehavioral Evaluation System (NES)	5 nights; 2 test sessions; 2 testing times: morning 08:00–09:00 h, 12:00–13:00h; test duration: 30–45 min	"Good" and "poor" sleepers, ↓performance in NES for "poor" sleepers, especially younger group, also ↑rates of behavioural problems
Steenari et al.[44]	$n = 60$ 31 f, 29 m 6–13 yrs	Auditory/visual working memory	Actigraphy, parents' logs, n-back task paradigm	72 h actigraphy, started at least one night before first experiment, continuously used during experimental period; auditory and visual tasks assessed on separate days	↓sleep efficiency and ↑sleep latency ↑incorrect responses, ↓sleep duration affected tasks at higher load only
Oginska & Pokorski[45]	$n = 432$ 191 adolescents 14–16 yrs 115 students 20–27 yrs 126 employees 30–45 yrs	Problems with memory	Questionnaires: declared need of sleep, self-reported sleep length, sleep index (= actual sleep length on an average day: individual sleep need), chronic fatigue scale (8 fatigue symptoms, 4 mood items, 3 cognitive items), Epworth Sleepiness Scale	None	Problems with memory in 18.3% of the adolescents, correlated + with sleep need and − with sleep index
Buckhalt et al.[46]	$n = 166$ 74 m, 92 f 7–11 yrs	Short-term memory: memory span, auditory working memory	Actigraphy, sleep diaries, School Sleep Habits Survey; 6 tasks from Woodcock-Johnson III (verbal comprehension, concept formation, visual matching, numbers reversed, auditory working memory, decision speed), reaction time tasks	Children's sleep was examined during the regular academic year; actigraphy for 7 consecutive nights; parents' diary on child's bedtime and wake-up time; on day 8 test battery	Sleepiness and sleep/wake problems correlated with ↓levels of cognitive performance, socioeconomic status moderated effects
Dworak et al.[47]	$n = 11$ 11 m 13.45 ± 1.04 yrs 1 drop-out	Visual and verbal memory	PSG, sleep diaries, visual and verbal memory test (VVM)	Control condition: children adhered to normal daily patterns but were not allowed to watch television or play computer games Computer game playing group: children played a computer game for 60 min Television viewing group: children watched a subjectively exciting video film memory testing: 4–5 h before bedtime	Computer games: ↓SWS, ↓verbal memory, ↑sleep latency and stage 2 Television watching: ↓Sleep efficiency

Abbreviations: m, male; f, female; yrs, years; h, hour; min, minute; PSG, polysomnography; SWS, slow wave sleep; ↑ increased; ↓ decreased.

Table 2
Studies with partial sleep deprivation.

Author	Sample	Memory type	Methods, measurements	Experimental conditions	Results
Carskadon et al.[49]	$n = 12$ 8 m, 4 f 11.7–14.6 yrs	Working memory, vigilance	PSG, MSLT, subjective sleepiness performance test battery (Wilkinson addition test, Williams word memory test, listening attention task)	3 days of adaptation; baseline night (10 h sleep, 22:00–08:00 h); sleep deprivation night (4 h sleep, 04:00–08:00 h); recovery night (10 h sleep, 22:00–08:00 h); 60 min performance test batteries were given daily at 10:00 h, 14:00 h and 20:00 h; fourth test battery was added at 02:00 h on the restricted sleep night	No effects on the memory tasks, MSLT showed ↑Sleepiness
Randazzo et al.[50]	$n = 16$ 7 m, 9 f 10–14 yrs	Verbal, visual, general memory	PSG, MSLT, battery of performance (WRAML, TTCT, CCT, WCST, CVLT) and sleepiness measures	Sleep restriction (5 h in bed) for one night, in the sleep laboratory, followed by daytime testing Control group: 11 h in bed (21:00–08:00 h); sleep-restricted group: 5 h in bed (03:00–08:00 h).	Sleep restriction: ↓Latencies in MSLT, verbal creativity (TTCT) and abstract thinking (WCST) were affected, none of the low cognitive load measures were affected
Sadeh et al.[51]	$n = 77$ 39 m, 38 f (neuropsychological data $n = 72$) 9.1–12.2 yrs	Visual memory, working memory	Actigraphy, daily sleep-wake diaries, Neuropsychological Evaluation System (NES)	Days 1 & 2: regular sleep; days 3–5: $n = 40$ went to sleep 1 h earlier = sleep extension group (SEG); $n = 37$ went to sleep 1 h later than regular bedtime = sleep restriction group (SRG); neuropsychological testing on day 1 or 2 (baseline) 08:00–10:00 h and on day 6 (after 3 consecutive nights of required alteration of sleep schedule) 08:00–10:00 h	Age and gender differences for sleep parameters (older ↓sleep time, ↑sleep latency, girls better sleepers), SEG improved in digit span, continuous performance and reaction time
Beebe et al.[87]	$n = 6$ 4 m, 2 f mean age 15.3 +/− 0.7 years	Attention, working memory	actigraphy, sleep self reports, parents' observations, fMRI scans, n-back task paradigm	3 week protocol: 1 baseline week, followed in random order by 1 week of sleep restriction (SR, 6.5 h time in bed) and 1 week of healthy duration (HD, 10 h time in bed); neuropsychological testing during fMRI monitoring in the morning after each experimental week	Comparable n-back performance between the SR and HD; however, relative to HD, in the SR condition subjects showed greater activation in task positive areas and more deactivation in task negative areas

Abbreviations: m, male; f, female; yrs, years; h, hour; min, minute; PSG, polysomnography, MSLT, multiple sleep latency test; ↑ increased; ↓ decreased; WRAML, Wide Range Assessment of Memory and Learning; TTCT, Torrance Test of Creative Thinking; CCT, Children's Category Test; WCST, Wisconsin Card Sorting Test; CVLT, California Verbal Learning Test.

Table 3
Studies with total sleep deprivation.

Author	Sample	Memory type	Methods, measurements	Experimental conditions	Results
Carskadon et al.[52]	$n = 9$ 6f, 3m 11–3.2 yrs	Working memory	PSG, MSLT, performance test battery (Wilkinson addition test, Williams word memory test, listening attention task, serial alternation task)	1 adaptation day, 2 baseline nights, 1 sleep deprivation night, 2 recovery days (10 h sleep, 22:00–08:00 h); performance tests daily at 10:00 h, 14:00 h and 20:00 h; during sleep deprivation, additionally at 02:00 h and 06:00 h	↑ Sleepiness, ↓ sleep latency in MSLT, addition test ↓ number attempted, word memory ↓ words recalled
Gais et al.[53]	Experiment 1: $n = 12$ 6m, 6f 17.4 ± 0.2 yrs Experiment 2: $n = 14$ males 18.1 ± 0.2 yrs	Declarative memory consolidation	4 different lists of 24 pairs of English–German vocabulary items	Experiment 2: *sleep condition:* learning and first recall at 20:00 h; 2 nights with regular bedtime at home; *sleep deprivation condition:* learning and first recall at 20:00 h; 1 night with total sleep deprivation under observation; at 06:00 h, sleep-deprived subjects were allowed to go home, where they slept during daytime, then recovery night; second recall in both conditions 48 h after initial learning at 08:00 h.	↑ Word recall

Abbreviations: m, male; f, female; yrs, years; h, hour; PSG, polysomnography; MSLT, multiple sleep latency test; ↑ increased; ↓ decreased.

compared to equal periods of daytime wakefulness. Consistent with the two-process model of sleep-related memory consolidation,[59] declarative memory consolidation specifically benefited from high percentages of NREM sleep (Tables 4 and 5).

Wilhelm and co-workers[57] extended the work by comparing the effects of nocturnal sleep versus daytime wakefulness on declarative memory consolidation (word-pair associates) and procedural memory consolidation (finger sequence tapping) in children (6–8 years) and adults (Table 4). As in the study by Backhaus et al.[56] recall of declarative memories was enhanced when sleep followed learning. However, in contrast to the hypothesis and to findings in adults, in children procedural performance was impaired after periods of nocturnal sleep in comparison to periods of daytime wakefulness. The authors concluded that sleep-related consolidation of distinct memory systems might depend on developmental stage. None of the standard sleep parameters derived from polysomnographic monitoring were significantly associated with memory consolidation in both age groups. The authors argued that time *per se* spent in certain sleep stages does not reflect neural processes that mediate memory consolidation.

Further support for decreased implicit performance after sleep in children comes from a study by Fischer and colleagues.[55] This group examined effects of sleep on implicit memory (serial reaction time task) in fourteen 7–11 year-old children and twelve 20–30 year old adults. Their performance was tested before and after retention periods of equal duration encompassing either daytime wakefulness or nocturnal sleep. Participants in both conditions were generally faster (grammatical and non-grammatical trials) at retesting compared to initial performance (Table 4). In both conditions, response times were faster in grammatical trials. In contrast to adults, sleep in children lead to a decrease in the reaction time difference between grammatical and non-grammatical trials, whereas across the wake interval the reaction time difference remained nearly unchanged. The authors speculated that the observed relative deterioration of implicit performance after sleep reflects a preferential effect of sleep toward the enhancement of explicit aspects of task performance in children that interferes with implicit performance gains.

Extending the findings on memory to subsequent levels of integration, Gomez et al.[54] investigated the effects of sleep on language learning in infants (Table 4). Fifteen-month-old infants were familiarised with an artificial language 4 h prior to a lab visit. One group napped during the interval between familiarisation and test. The other group did not nap. Whereas infants without nap showed a simple memory effect, infants who napped appeared to remember a more abstract relation of the presented auditory strings. The authors state that there seemed to be a qualitative change in memory following sleep, allowing a greater flexibility and generalisation in learning, beyond the level of mere consolidation.

Neural correlates

Already back in 1988, Horne[60] described that functions related to the prefrontal cortex (PFC) play a crucial role in working memory and exhibit the most pronounced deficits after sleep deprivation. Dahl's developmental model for the development of sleep and arousal regulation also attributes a central role to the PFC.[30] As in adults, sleep restriction or sleep loss in children and adolescents seems to preferentially affect those tasks that require effective PFC functioning. This applies particularly to tasks that are abstract or complex.[61] This model is consistent with findings by Sadeh et al.[51] where sleep restriction led to reduced neurobehavioral functioning

Table 4
Studies with sleep-wake conditions.

Author	Sample	Memory type	Methods, measurements	Experimental conditions	Results
Gomez et al.[54]	$n = 48$ 8m, 8 f in each condition 15 months	Veridical memory, memory enhancement, memory abstraction and reorganization in language-learning	Learning of artificial language, actigraphy, log of infant's activity, experimenter visited each infant's home 4 h prior to testing, testing in the laboratory using the head-turn preference procedure.	No-nap condition: were not deprived of sleep, but were scheduled at times that were not expected to coincide with the usual time of their nap Nap condition: were scheduled such that their usual naptime would occur between exposure and test Nap-control condition: infants also napped between exposure and test, but unlike the other groups, they were exposed to a language with only a small set of elements	No-nap condition: ↑ preference for familiar over unfamiliar strings Nap condition: ↑looking-time difference, qualitative change in memory, greater flexibility in learning
Gais et al.[53]	Experiment 1: $n = 12$ 6 m, 6 f 17.4 ± 0.2 yrs	Declarative memory consolidation	24-pair English–German vocabulary lists	Experiment 1: *4 experimental conditions:* morning-to-evening, evening-to-morning, evening-to-evening, morning-to-morning; Subjects learned on each occasion 1 of 4 24-pair English–German vocabulary lists; learning either at 08:00 h or at 20:00 h; recall immediately after learning, after 24 h or 36 h, either 08:00 h or 20:00 h	Morning-learning: ↑rate of forgetting no difference for different retention intervals or recall time
Fischer et al.[55]	$n = 26$ 14 children, 7 m, 7 f; 7–11 yrs 12 adults, 4 f, 8 m 20–30 yrs	Implicit memory	Serial reaction time task (SRTT), PSG, subjective estimating of tiredness, activation, concentration	Sleep condition: Initial learning at 20:00 h for children and 21:00 h for adults (lasted about 60 min); children went to bed at 22:00 h adults at 23:00 h; retesting at 07:30 h Wake condition: Initial learning at 08:00 h for children and 09:00 h for adults; retesting at 19:30 h	Sleep condition: ↓Implicit knowledge (in contrast to adults)
Backhaus et al.[56]	$n = 27$ 13 f, 14 m 9–12 yrs	Declarative memory consolidation	Word pair associates task, ambulatory polysomnography system, actigraphy, measurements were performed at the children's home.	Sleep-wake condition: Learning before children went to bed at their usual bedtime; retrieval 1 next morning; retrieval 2 on the evening of the same day after a period of daytime wakefulness that had the same duration as the child's habitual nocturnal sleep period Wake-sleep condition: Learning in the morning; retrieval 1in the evening of the same day after a period of wake-time followed by a night of regular sleep; retrieval 2 on the next morning	↑Retention of word pairs after sleep, in both conditions
Wilhelm et al.[57]	$n = 30$ 15 children, 9 f, 6 m, 6–8 yrs 15 adults, 13 f, 2 m	Declarative and procedural	Word pair associates task, 2D object location, finger sequence tapping, home PSG, subjective estimation of tiredness and motivation	Sleep condition: normal sleep; Learning at 20:00 h for children and 22:00 h for adults; bedtime at the habitual time for children (19:30–21:30 h) and adults (22:00–00:00 h); wake-up at usual time; retrieval 60 min later; interval 11 h Wake condition: Learning in the morning 60 min after awakening; retrieval after a retention interval of wakefulness of 11 h; normal daily schedules and parents' continuous recording of children's activities during wake retention interval	Sleep condition: ↑Retention of word pairs, ↑recall of card locations, Wake condition: improved performance in finger tapping (in contrast to adults)

Abbreviations: m, male; f, female; yrs, years; h, hour; min, minutes; PSG, polysomnography; ↑ increased; ↓ decreased.

Table 5
Description of tests and measures used in the selected studies in alphabetical order.

Tests author	Description	Outcome
2D object location task (OLT) Rasch et al.[69]	The 2D OLT resembles the game "concentration" and consists of 15 card-pairs showing coloured pictures of different animals and everyday objects; a cued recall procedure is repeated until the criterion is reached (40% and 60% correct responses in children and adults respectively); at retrieval testing after the retention interval, all card-pairs are tested once using the same cued recall procedure.	Number of correct recalls
California Verbal Learning Test (CVLT) Delis et al.[70]	The CVLT assesses recall memory of 14 words during 5 identical trials and a sixth trial following presentation of an interference list; it measures how verbal learning occurs and how much material is learned, incorporates both short-delay and long-delay recall trials to assess retention	Total score across all trials
Children's Category Test (CCT) Boll[71]	The child needs to identify the connecting idea or principle for 1 or more shapes, lines or figures shown on a card; 4 possible answers are provided	Number of errors
English–German vocabulary list Gais et al.[53]	Subjects learn a 24-pair English–German vocabulary list, presented on paper within 10 min; lists consist of 10 dissimilar and 5 cognate nouns and 5 verbs, 2 pairs of nouns in the beginning and at the end of each list are excluded from later analysis to rule out recency and primacy effects; immediately after learning, recall is tested to see how many words are initially retained; recall is tested again after 24 h or 36 h in written format with the English words given in a different order than during the original presentation	Number of correctly remembered words, average individual percent change in recall performance across the retention interval
Finger sequence tapping task Walker, et al.[72]	With slight modifications to adjust it for use in young children (Wilhelm et al.[57]); it requires the subject to repeatedly press one of two five-element sequences (4-1-3-2-4 and 2-3-1-4-2) on a keyboard with the fingers of the non-dominant hand; subjects are instructed to repeatedly type the sequence as fast and as accurately as possible; at learning, subjects perform 12 30-sec trials each interrupted by 30-sec breaks; retrieval testing includes 3 trials after 1 warm-up trial.	Correct sequences, time
Listening attention task Evans-Pritchard[73]	10 min reading from a series of children's books; subjects have to press a button every time they hear certain keywords	Total number of keywords missed
n-back tasks Anourova et al.[74]	The n-back task has been widely used in human neuroimaging and psychophysical studies (e.g., Anourova et al.[74]); the memory load can be varied by increasing the value of "*n*" and thus the number of items that have to be kept in mind while maintaining other features of the task unchanged (e.g., the number of stimuli presented over time and the number and quality of responses); the memory load is modulated by changing the instruction to perform the task	Percentage of incorrect, missed and multiple responses; reaction time
Neurobehavioural Evaluation System (NES) Letz[75]	A test developed to detect variations in neuropsychological functioning; adapted for children (e.g., Dahl et al.[30]); 6 age appropriate tests: finger tapping (motor speed); simple reaction time; continuous performance (visual attention); symbol-digit substitution (see SDS); visual digit span test; serial digit learning test	Number of taps; reaction time; omission and commission errors; response latency; error score
Serial alternation task Lubin et al.[76]	Subjects are instructed to tap 2 switches regularly and alternately at a steady pace for 15 min	Cumulative score of number of sec failed to tap
Serial digit learning test Letz[75]	Recall a long sequence of single digits presented in succession; the same sequence of digits is repeated until either the child recalls the entire sequence correctly or the maximum of 8 trials is reached	Number of correct recall of sequences
Serial Reaction Time Task (SRTT) Thomas et al.[77]; Peigneux et al.[78]	The SRTT is a paradigm that has been widely used to assess implicit memory function in adults (Thomas et al.[77]; Peigneux et al.[78]); it is basically a choice reaction time task that requires the subject to react as fast and accurately as possible to a visual cue appearing on a screen at one of several possible positions within a horizontal array; each screen position spatially corresponds to a key on a response box; unknown to the subject, the sequence of target positions is not randomly determined but follows a set of rules that can be either deterministic or probabilistic	Number of correct responses, time
Subtest 'auditory working memory' and 'numbers reversed' of the Woodcock-Johnson III Tests of Cognitive Abilities Woodcock (WJ III), McGrew & Mather[79]	'Auditory working memory' measures short-term auditory memory and working memory; in addition, divided attention is required; a series of numbers mixed with words is presented, and subjects must recall the series reporting the words in correct order first, then the numbers	Test scores
	The WJ III measures general intellectual ability and specific cognitive abilities; 'numbers reversed' is a test of short-term memory span and also engages working memory as the numbers must be held in working memory while performing a mental operation (reversing the sequence)	Test scores
Symbol Digit Substitution Task (SDS) Letz[75]	9 pairs of matched symbols and digits are painted at the top of a screen; child is requested to press the digits on the keyboard corresponding to a test set of the 9 symbols presented in mixed order	Correct responses
Torrance Tests of Creative Thinking (TTCT) Torrance[80]	A verbal and a figural version; the verbal version assesses creative development by determining fluency, originality and flexibility, figural creativity involves communicating unusual and unique ideas through drawing	Test scores
Visual and Verbal Memory test (VVM) Schellig & Schaechtele[81]	The VVM tests short and long-term memory of visuo-spatial and verbal material; the decrease in memory performance and the rate of forgetting can be calculated; the VVM contains two subtests: in the subtest 'city map' subjects have to memorize the course of a route and then mark it on the same map during recall, in the subtest 'construction' a description of a building is presented to participants, worded in syntactically simple sentences and participants have to learn names, numbers, and propositional contents.	Test scores

Visual digit span test Letz[75]	Recall presented sequences of digits; repeat the sequence on the computer keyboard forward and backward	Average response latency time
Wide Range Assessment of Memory and Learning (WRAML) Adams & Sheslow[82]	The WRAML is designed to assess memory and learning functions across the school years (5–17 yrs); scales: Verbal Memory Index, Visual Memory Index, Learning Index, General Memory Index	Test scores
Wilkinson Addition Test Wilkinson[83]	Subjects have to add columns of 5 two-digit numbers	Number of problems attempted, correct responses
Williams Word Memory Test Williams et al.[84]	A sequence of 25 four-letter words; words are read at a rate of one every 10 s; subjects are asked to repeat them in any order; a shortened form of the WWMT was used by Carskadon et al.[49,52]	Number of correct recalls
Wisconsin Card Sorting Test (WCST) Heaton[85]	Subjects have to identify 3 predetermined criterion principles; they are presented with 4 different stimulus cards and are instructed to match each subsequent card to the stimulus cards; correct and incorrect placements are pointed out for learning	Test scores
Word-pair associate learning task Plihal & Born[86]	Subjects learn a list of word pairs; the experimenter reads out loud all word pairs on the list, then the first (cue) word of each pair in random order, and the subject has to name the associated word (with no explicit time limit); procedure is repeated until the subject reaches a criterion of 60% correct responses; at retrieval testing after the retention interval, the same cued recall procedure is used with each word-pair tested once.	Number of correct recalls

Abbreviations: yrs, years; h, hours; min, minutes; sec, seconds.

(including vigilance, working memory, and response inhibition), and by Steenari et al.[44] who found an impairment only for working memory tasks with high cognitive load. Beebe et al.[87] reported preliminary findings from a small sample fMRI study on healthy adolescents who completed a working memory task in the context of a chronic sleep restriction experiment. These results show – just as prior studies did for adults – that even when performance is maintained, the involved prefrontal brain regions display increased activation, indicating that more effort is required for successfully completing the task.[54]

Some studies have begun to elucidate potential neural underpinnings of memory consolidation during sleep.

Animal[62] and human studies[63] indicate that newly acquired memories are replayed and further processed during sleep, presumably contributing to brain plasticity underlying long-term memory formation.[64] Other studies demonstrate that sleep-specific brain activity patterns, such as EEG sleep spindles[65] or ponto-geniculo-occipital (PGO) waves related to rapid eye movements,[66] foster the transition from unstable memories into more durable ones. An alternative hypothesis (synaptic homeostasis hypothesis of sleep[67]) proposes that synapses strengthened during daytime wakefulness undergo a process of generalized downscaling during sleep, specifically during EEG slow wave activity (SWA), refining the information/noise ratio in neural networks and restoring the brain's ability to acquire new information under conditions of limited energy and space. To our knowledge, no studies have further investigated potential neural mechanisms of sleep-related memory and the impact of developmental aspects in children. Combined behavioural, electrophysiological as well as functional and structural brain imaging studies are needed to further elucidate the interplay between sleep and memory formation in children and adolescents.

Summary and outlook

Most studies reviewed here support the hypothesis that sleep facilitates memory encoding, working memory and long-term memory consolidation not only in adults but also in children and adolescents. Some studies suggest that sleep might be of particular importance for the completion of more demanding and complex tasks, or that it becomes more important under additional adverse conditions such as lower socioeconomic status. However, compared to a solid body of data derived from studies in animals and healthy adults, the field of sleep and memory research in children and adolescents is just beginning to evolve and significant research questions remain.

Importantly, future studies should systematically assess the impact of sleep on distinct stages of memory, including encoding, working memory, consolidation, retrieval, reconsolidation or higher-level integration. Furthermore, different memory systems need to be investigated separately in children, specifically since preliminary findings suggest that implicit memories, shown to be enhanced by sleep in adults, do not seem to benefit from periods of sleep in children. While the concept of distinct memory systems offers a testable first approach, additional studies are needed to transfer the basic findings to complex real life situations where distinct memory systems rarely operate in isolation.

Most studies reviewed here used tasks that were originally developed for adults or for pathological conditions, such as the Neurobehavioural Evaluation System used by Sadeh et al.[43] Future research will crucially hinge on using or developing age-adapted memory tasks that are sensitive enough to measure various degrees of sleep-related alterations in healthy children and adolescents.

Based on emerging insights into the effects of sleep on different memory stages and systems, it would be interesting to investigate the impact of various parameters potentially modulating sleep and memory. These include developmental stages, gender differences, socioeconomic status, or other domains of cognitive functioning, such as alertness or motivation.

It is particularly necessary to further investigate and to control for potential circadian influences. In addition, it has become increasingly evident that memory formation can occur during both sleep and wakefulness,[68] and therefore it will be important to further elucidate the specific impact of sleep- and wakefulness-related brain activity. Studies that control for or experimentally vary the level of post-learning sensory and motor activity (interference) will help differentiate between sleep-specific effects and the effects of reduced levels of interference during quiet wakefulness. In addition, animal research and studies on children and adolescents employing a variety of electrophysiological and brain imaging methods will be required to better understand the neural mechanisms underlying the impact of sleep on memory in children and adolescents. Finally, further in-depth investigations on the effects of both sleep disruption and sleep deprivation as well as on sleep extension are called for. Especially research with sleep extension paradigms should be of interest, given the fact that at least one study showed its beneficial effects[51] and most adolescents sleep less than the recommended time.[41,36]

In summary, the current review supports the hypothesis that sleep fosters at least some aspects of working memory and memory consolidation in healthy children and adolescents. Further investigation of the impact of sleep on memory may have the potential to provide significant steps towards the development of new effective teaching and learning strategies, such as the modulation of sleep/wake behaviour during periods of learning, and issuing recommendations to teachers, parents, children and adolescents about sleep and memory as two integral parts of health and functioning.

Practice points

1. Recent evidence supports the idea that sleep promotes memory encoding, working memory and memory consolidation in children and adolescents.
2. Some evidence indicates that abstract and complex tasks involving higher brain functions are more profoundly impaired after sleep deprivation than simple memory tasks.
3. Preliminary data suggests that children seem to tolerate a single night of sleep restriction relatively well with relevant differences only emerging after prolonged periods of restricted sleep or total sleep deprivation.
4. Sleep-related memory consolidation in children may show significant differences compared to sleep-related memory consolidation in adults. Specifically, procedural memory consolidation may not profit from sleep to the same extent as it does in adults.
5. Preliminary findings suggest that extensive media consumption prior to sleep might have a detrimental effect on sleep and related memory consolidation in children.
6. A further investigation of the relationship between sleep and memory in children and adolescents could become the foundation for issuing guidelines to teaching, learning and public health policy.

Research agenda

1. Future studies are needed to systematically investigate the impact of sleep on distinct memory stages (encoding, consolidation, retrieval) and systems (declarative and non-declarative systems as along with their subsystems) in children and adolescents.
2. Additional work is needed to assess the amount of sleep restriction or sleep loss that can be tolerated or that leads to negative consequences (dose-response studies). This should aid in better understanding potential compensatory mechanisms.
3. Further research is required to investigate the impact of a host of variables that potentially modulate sleep-related memory consolidation, such as developmental stage, gender differences, or socioeconomic status.
4. Additional studies are necessary to delineate the impact of homeostatic (prior-to-sleep) and circadian (time-of-the-day) effects on sleep and memory.
5. Additional studies that experimentally vary the post-learning level of sensory and motor activity (interference) during states of wakefulness will be crucial to discern the impact of sleep-specific brain activity patterns on memory from effects of reduced interference.
6. Finally, future research may develop novel strategies concerning the interplay between sleep and memory in children and adolescents, e.g., recommendations for learning phases before sleep, daytime naps after learning or a longer night's sleep on school days.

References

1. Born J, Rasch B, Gais S. Sleep to remember. *Neuroscientist* 2006;**12**(5):410–24.
2. Marshall L, Born J. The contribution of sleep to hippocampus-dependent memory consolidation. *Trends Cogn Sci* 2007;**11**(10):442–50.
3. Stickgold R, Walker MP. Sleep and memory: the ongoing debate. *Sleep* 2005;**28**(10):1225–7.
4. Stickgold R, Walker MP. Memory consolidation and reconsolidation: what is the role of sleep? *Trends Neurosci* 2005;**28**(8):408–15.
5. Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. *Semin Neurol* 2005;**25**(1):117–29.
6. Maquet P. The role of sleep in learning and memory. *Science* 2001;**294**(5544):1048–52.
7. Pilcher JJ, Huffcutt AI. Effects of sleep deprivation on performance: a meta-analysis. *Sleep* 1996;**19**(4):318–26.
8. Ebert Jr CS, Drake AF. The impact of sleep-disordered breathing on cognition and behavior in children: a review and meta-synthesis of the literature. *Otolaryngol Head Neck Surg* 2004;**131**(6):814–26.
9. Garetz SL. Behavior, cognition, and quality of life after adenotonsillectomy for pediatric sleep-disordered breathing: summary of the literature. *Otolaryngol Head Neck Surg* 2008;**138**(1 Suppl.):S19–26.
10. Hill CM, Hogan AM, Karmiloff-Smith A. To sleep, perchance to enrich learning? *Arch Dis Child* 2007;**92**(7):637–43.
11. Kheirandish L, Gozal D. Neurocognitive dysfunction in children with sleep disorders. *Dev Sci* 2006;**9**(4):388–99.
12. Mitchell RB, Kelly J. Outcomes and quality of life following adenotonsillectomy for sleep-disordered breathing in children. *ORL J Otorhinolaryngol Relat Spec* 2007;**69**(6):345–8.
13. Curcio G, Ferrara M, De Gennaro L. Sleep loss, learning capacity and academic performance. *Sleep Med Rev* 2006;**10**(5):323–37.
14. Mitru G, Millrood DL, Mateika JH. The impact of sleep on learning and behavior in adolescents. *Teach Coll Rec* 2002;**104**(4):704–26.
15. Walker MP, Stickgold R. Sleep, memory and plasticity. *Annu Rev Psychol* 2006;**57**:139–66.
16. Baddeley A. Working memory: looking back and looking for forward. *Nat Rev Neurosci* 2003;**4**(10):829–39.
17. Squire LR, Zola SM. Structure and function of declarative and nondeclarative memory systems. *Proc Natl Acad Sci U S A* 1996;**93**(24):13515–22.
18. Walker MP, Stickgold R. Sleep-dependent learning and memory consolidation. *Neuron* 2004;**44**(1):121–33.
19. Brehmer Y, Li SC, Muller V, von Oertzen T, Lindenberger U. Memory plasticity across the life span: uncovering children's latent potential. *Dev Psychol* 2007;**43**(2):465–78.

20. Li SC, Brehmer Y, Shing YL, Werkle-Bergner M, Lindenberger U. Neuromodulation of associative and organizational plasticity across the life span: empirical evidence and neurocomputational modeling. *Neurosci Biobehav Rev* 2006;**30**(6):775–90.
21. Scherf KS, Sweeney JA, Luna B. Brain basis of developmental change in visuospatial working memory. *J Cogn Neurosci* 2006;**18**(7):1045–58.
22. Kuboshima-Amemori S, Sawaguchi T. Plasticity of the primate prefrontal cortex. *Neuroscientist* 2007;**13**(3):229–40.
23. Hobson JA, Pace-Schott EF. The cognitive neuroscience of sleep: neuronal systems, consciousness and learning. *Nat Rev Neurosci* 2002;**3**(9):679–93.
24. Anders TF. Infant sleep, nighttime relationships, and attachment. *Psychiatry* 1994;**57**(1):11–21.
25. Ohayon M, Carskadon M, Guilleminault C, Vitiello M. 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**(7):1255–73.
26. Jenni OG, Borbély AA, Achermann P. Development of the nocturnal sleep electroencephalogram in human infants. *Am J Physiol Regul Integr Comp Physiol* 2004;**286**:R528–38.
27. Jenni OG, Carskadon MA. Spectral analysis of the sleep electroencephalogram during adolescence. *Sleep* 2004;**27**:774–83.
28. Huber R. High-density sleep EEG recordings during adolescence. *J Sleep Res* 2008;**17**(s1):S39.
29. Giedd JN. Structural magnetic resonance imaging of the adolescent brain. *Ann N Y Acad Sci* 2004;**1021**:77–85.
30. Dahl RE. The impact of inadequate sleep on children's daytime cognitive function. *Semin Pediatr Neurol* 1996;**3**(1):44–50.
31. Dang-Vu TT, Desseilles M, Peigneux P, Maquet P. A role for sleep in brain plasticity. *Pediatr Rehabil* 2006;**9**(2):98–118.
32. Carskadon MA, Harvey K, Duke P, Anders TF, Litt IF, Dement WC. Pubertal changes in daytime sleepiness. *Sleep* 1980;**2**(4):453–60.
33. Carskadon MA. Patterns of sleep and sleepiness in adolescents. *Pediatrician* 1990;**17**(1):5–12.
34. Carskadon MA, Wolfson AR, Acebo C, Tzischinsky O, Seifer R. Adolescent sleep patterns, circadian timing, and sleepiness at a transition to early school days. *Sleep* 1998;**21**(8):871–81.
35. Carskadon MA, Acebo C, Seifer R. Extended nights, sleep loss, and recovery sleep in adolescents. *Arch Ital Biol* 2001;**139**(3):301–12.
36. Laberge L, Petit D, Simard C, Vitaro F, Tremblay RE, Montplaisir J. Development of sleep patterns in early adolescence. *J Sleep Res* 2001;**10**(1):59–67.
37. Taylor DJ, Jenni OG, Acebo C, Carskadon MA. Sleep tendency during extended wakefulness: insights into adolescent sleep regulation and behavior. *J Sleep Res* 2005;**14**(3):239–44.
38. Lazaratou H, Dikeos DG, Anagnostopoulos DC, Sbokou O, Soldatos CR. Sleep problems in adolescence. A study of senior high school students in Greece. *Eur Child Adolesc Psychiatry* 2005;**14**(4):237–43.
39. LeBourgeois MK, Giannotti F, Cortesi F, Wolfson A, Harsh J. Sleep hygiene and sleep quality in Italian and American adolescents. *Ann N Y Acad Sci* 2004;**1021**:352–4.
40. Liu X, Liu L, Owens JA, Kaplan DL. Sleep patterns and sleep problems among schoolchildren in the United States and China. *Pediatrics* 2005;**115**(1 Suppl.):241–9.
41. Wolfson AR, Carskadon MA. Sleep schedules and daytime functioning in adolescents. *Child Dev* 1998;**69**(4):875–87.
42. Carskadon MA, Acebo C, Jenni OG. Regulation of adolescent sleep: implications for behavior. *Ann N Y Acad Sci* 2004;**1021**:276–91.
43. Sadeh A, Gruber R, Raviv A. Sleep, neurobehavioral functioning, and behavior problems in school-age children. *Child Dev* 2002;**73**(2):405.
44. Steenari MR, Vuontela V, Paavonen EJ, Carlson S, Fjallberg M, Aronen E. Working memory and sleep in 6- to 13-year-old schoolchildren. *J Am Acad Child Adolesc Psychiatry* 2003;**42**(1):85–92.
45. Oginska H, Pokorski J. Fatigue and mood correlates of sleep length in three age-social groups: school children, students, and employees. *Chronobiol Int* 2006;**23**(6):1317–28.
46. Buckhalt JA, El Sheikh M, Keller P. Children's sleep and cognitive functioning: race and socioeconomic status as moderators of effects. *Child Dev* 2007;**78**(1):213–31.
47. Dworak M, Schierl T, Bruns T, Strüder HK. Impact of singular excessive computer game and television exposure on sleep patterns and memory performance of school-aged children. *Pediatrics* 2007;**120**(5):978–85.
48. Tassi P, Muzet A. Sleep inertia. *Sleep Med Rev* 2000;**4**:341–53.
49. Carskadon MA, Harvey K, Dement WC. Acute restriction of nocturnal sleep in children. *Percept Mot Skills* 1981;**53**(1):103–12.
50. Randazzo AC, Muehlbach MJ, Schweitzer PK, Walsh JK. Cognitive function following acute sleep restriction in children ages 10–14. *Sleep* 1998;**21**(8):861–8.
51. 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**(2):444–55.
52. Carskadon MA, Harvey K, Dement WC. Sleep loss in young adolescents. *Sleep* 1981;**4**(3):299–312.
53. Gais S, Lucas B, Born J. Sleep after learning aids memory recall. *Learn Mem* 2006;**13**:259–62.
54. Gomez RL, Bootzin RR, Nadel L. Naps promote abstraction in language-learning infants. *Psychol Sci* 2006;**17**(8):670–4.
55. Fischer S, Wilhelm I, Born J. Developmental differences in sleep's role for implicit off-line learning: comparing children with adults. *J Cogn Neurosci* 2007;**19**(2):214–27.
56. Backhaus J, Hoeckesfeld R, Born J, Hohagen F, Junghanns K. Immediate as well as delayed post learning sleep but not wakefulness enhances declarative memory consolidation in children. *Neurobiol Learn Mem* 2008;**89**(1):76–80.
57. Wilhelm I, Diekelmann S, Born J. Sleep in children improves memory performance on declarative but not procedural tasks. *Learn Mem* 2008;**15**:373–7.
58. Rauchs G, Desgranges B, Foret J, Eustache F. The relationships between memory systems and sleep stages. *J Sleep Res* 2005;**14**:123–40.
59. Plihal W, Born J. Effects of early and late nocturnal sleep on declarative and procedural memory. *J Cogn Neurosci* 1997;**9**(4):534–48.
60. Horne JA. Sleep loss and "divergent" thinking ability. *Sleep* 1988;**11**:528–36.
61. Horne JA. Human sleep, sleep loss, and behaviour: implications for the prefrontal cortex and psychiatric disorder. *Br J Psychiatry* 1993;**162**:413–9.
62. Wilson MA, McNaughton BL. Reactivation of hippocampal ensemble memories during sleep. *Science* 1994;**265**:676–85.
63. Maquet P, Laureys S, Peigneux P. Experience-dependent changes in cerebral activation during human REM sleep. *Nat Neurosci* 2000;**3**:831–6.
64. Ribeiro S, Nicolelis MA. Reverberation, storage, and postsynaptic propagation of memories during sleep. *Learn Mem* 2004;**11**:686–96.
65. Schabus M, Gruber G, Parapatics S. Sleep spindles and their significance for declarative memory consolidation. *Sleep* 2004;**27**:1479–85.
66. Datta S, Mavanji V, Ulloor J, Patterson EH. Activation of phasic pontine-wave generator prevents rapid eye movement sleep deprivation-induced learning impairment in the rat: a mechanism for sleep-dependent plasticity. *J Neurosci* 2004;**24**:1416–27.
67. Tononi G, Cirelli C. Sleep function and synaptic homeostasis. *Sleep Med Rev* 2006;**10**:49–62.
68. Paller KA, Voss JL. Memory reactivation and consolidation during sleep. *Learn Mem* 2004;**11**(6):664–70.
69. Rasch B, Buchel C, Gais S, Born J. Odor cues during slow-wave sleep prompt declarative memory consolidation. *Science* 2007;**315**:1426–9.
70. Delis D, Kramer J, Kaplan E, Ober B. *California verbal learning test – children's version: manual*. San Antonio: The Psychological Corporation, Harcourt Brace & Co.; 2008.
71. Boll T. *Children's category test: manual*. San Antonio: The Psychological Corporation, Harcourt Brace & Co.; 1993.
72. Walker MP, Brakefield T, Seidman J, Morgan A, Hobson JA, Stickgold R. Sleep and the time course of motor skill learning. *Learn Mem* 2003;**10**(4):275–84.
73. Evans-Pritchard E. *Peoples of the earth*. Suffern, NY: Danbury Press; 1972.
74. Anourova I, Rämä P, Alho K, Koivusalo S, Kahnari J, Carlson S. Selective interference reveals dissociation between auditory memory for location and pitch. *Neuroreport* 1999;**10**:3543–7.
75. Letz R. Use of computerised test batteries for quantifying neurobehavioral outcomes. *Environ Health Perspect* 1991;**90**:195–8.
76. Lubin A, Moses J, Johnson L, Naitoh P. The recuperative effects of REM and stage 4 sleep on human performance after complete sleep loss: experiment 1. *Psychophysiology* 1974;**11**:133–46.
77. Thomas KM, Hunt RH, Vizueta N, Sommer T, Durston S, Yang Y, et al. Evidence of developmental differences in implicit sequence learning: an fMRI study of children and adults. *J Cogn Neurosci* 2008;**16**:1339–51.
78. Peigneux P, Laureys S, Fuchs S, Destrebecqz A, Collette F, Delbeuck X, et al. Learned material content and acquisition level modulate cerebral reactivation during posttraining rapid-eye-movements sleep. *Neuroimage* 2003;**20**(2):125–34.
79. Woodcock RW, McGrew KS, Mather M. *Woodcock-Johnson III tests of cognitive ability*. Itasca NY: Riverside Publishing; 2001.
80. Torrance E. *Torrance test of creative thinking. Manual*. Bensenville, IL: Scholastic Testing Service, Inc.; 1990.
81. Schellig D, Schaechtele B. *Visueller und Verbaler Merkfähigkeitstest*. Hogrefe: Goettingen; 2001.
82. Adams D, Sheslow W. *Wide range assessment of memory and learning. Manual*. San Antonio: The Psychological Corporation, Harcourt Brace&Co; 1990.
83. Wilkinson RT. Sleep deprivation: performance tests for partial and selective sleep deprivation. In: Abt LE, Riess BF, editors. *Progress in clinical psychology*. New York: Grune & Stratton; 1968.
84. Williams HL, Gieseking CF, Lubin A. Some effects of sleep loss on memory. *Percept Mot Skills* 1966;**23**:1287–93.
85. Heaton R. *Wisconsin card sorting test: manual*. Odessa, FL: Psychological Assessment Resources, Inc; 1981.
86. Plihal W, Born J. Memory consolidation in human sleep depends on inhibition of glucocorticoid release. *Neuroreport* 1999;**10**(13):2741–7.
87. Beebe DW, DiFrancesco MW, Tlustos SJ, McNally KA, Holland SK. Preliminary fMRI findings in experimentally sleep-restricted adolescents engaged in a working memory task. *Behav Brain Funct* 2009;**5**:9.