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

Marta Kopasz a, Barbara Loessl a, Magdolna Hornyak a, b, Dieter Riemann a, Christoph Nissen a, Hannah Piosczyk a, Ulrich Voderholzer a, c, *

a Department of Psychiatry and Psychotherapy, University Medical Center Freiburg, Hauptstrasse 5, 79104 Freiburg, Germany
b Interdisciplinary Pain Center, University Medical Center Freiburg, Germany
c Roseneck Hospital for Behavioral Medicine, Prien, Germany

Keywords: Children Adolescents Sleep Neuropsychology Memory consolidation Learning

SUMMARY

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.

© 2009 Elsevier Ltd. All rights reserved.

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 adults5–7 and children with sleep disorders or other disorders affecting sleep.8–12 There are also thorough reviews on the association between sleep and academic performance13 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
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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{21} Visuo-spatial 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).\textsuperscript{21} The PFC itself develops columnar modules that form cognitive fields relevant for a specific cognitive function. These become reorganised through training.\textsuperscript{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.\textsuperscript{23} Compared to adulthood, childhood is characterised by a longer sleep duration and larger amounts of SWS and REM sleep.\textsuperscript{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.\textsuperscript{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.\textsuperscript{27} Using high-density sleep EEG, a lower frontal predominance of slow wave activity has been observed in children and adolescents compared to adults,\textsuperscript{28} possibly reflecting the late maturation of the frontal cortex.\textsuperscript{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.\textsuperscript{10,30} Animal studies have demonstrated that developmental sleep is critically involved in brain plasticity (for review see Dang-Vu et al.\textsuperscript{31}). In addition, the circadian timing of sleep changes with the onset of puberty: sleep-onset\textsuperscript{32–34} is delayed, especially around the age of 14–16 years, i.e., at the mid-to-late-pubertal stage.\textsuperscript{37} Despite cultural differences, many studies have shown that adolescents world-wide sleep significantly less than the recommended 9–10 h.\textsuperscript{31,38–40} 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.\textsuperscript{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.\textsuperscript{24,42}

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,\textsuperscript{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\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{45} 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 Pokorski45 (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-workers46 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 group52 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-workers51 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 adults58 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.67 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.59 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>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Memory type</th>
<th>Methods, measurements</th>
<th>Experimental conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sadeh et al. 43</td>
<td>( 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</td>
<td>Visual memory, working memory</td>
<td>Actigraphy, Child Behaviour Check List (parental reports), teachers’ report form, Neurobehavioral Evaluation System (NES)</td>
<td>5 nights; 2 test sessions; 2 testing times: morning 08:00–09:00 h, 12:00–13:00h; test duration: 30–45 min</td>
<td>“Good” and “poor” sleepers, ( \dagger ) performance in NES for “poor” sleepers, especially younger group, also ( \downarrow ) rates of behavioural problems</td>
</tr>
<tr>
<td>Steenari et al. 44</td>
<td>( n = 60 ) 31 f, 29 m 6–13 yrs</td>
<td>Auditory/visual working memory</td>
<td>Actigraphy, parents’ logs, n-back task paradigm</td>
<td>72 h actigraphy, started at least one night before first experiment, continuously used during experimental period; auditory and visual tasks assessed on separate days</td>
<td>( \dagger ) sleep efficiency and ( \uparrow ) sleep latency ( \uparrow ) incorrect responses, ( \downarrow ) sleep duration affected tasks at higher load only</td>
</tr>
<tr>
<td>Oginska &amp; Pokorski 45</td>
<td>( n = 432 ) 191 adolescents 14–16 yrs 115 students 20–27 yrs 126 employees 30–45 yrs</td>
<td>Problems with memory</td>
<td>Questionnaires: declared need of sleep, self-reported sleep length, sleep index (( \rightarrow ) 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</td>
<td>None</td>
<td>Problems with memory in 18.3% of the adolescents, correlated ( \rightarrow ) with sleep need and ( \rightarrow ) with sleep index</td>
</tr>
<tr>
<td>Buckhalt et al. 46</td>
<td>( n = 166 ) 74 m, 92 f 7–11 yrs</td>
<td>Short-term memory: memory span, auditory working memory</td>
<td>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</td>
<td>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</td>
<td>Sleepiness and sleep/wake problems correlated with ( \uparrow ) levels of cognitive performance, socioeconomic status moderated effects</td>
</tr>
<tr>
<td>Dworak et al. 47</td>
<td>( n = 11 ) 11 m 13.45 ± 1.04 yrs 1 drop-out</td>
<td>Visual and verbal memory</td>
<td>PSG, sleep diaries, visual and verbal memory test (VVM)</td>
<td>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</td>
<td>Computer games: ( \uparrow ) SWS, ( \uparrow ) verbal memory, ( \uparrow ) sleep latency and stage 2 Sleep efficiency</td>
</tr>
</tbody>
</table>

Abbreviations: m, male; f, female; yrs, years; h, hour; min, minute; PSG, polysomnography; SWS, slow wave sleep; \( \uparrow \) increased; \( \downarrow \) decreased.
<table>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Memory type</th>
<th>Methods, measurements</th>
<th>Experimental conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carskadon et al.</td>
<td>(n = 12) 8 m, 4 f 11.7–14.6 yrs</td>
<td>Working memory, vigilance</td>
<td>PSG, MSLT, subjective sleepiness performance test battery (Wilkinson addition test, Williams word memory test, listening attention task)</td>
<td>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</td>
<td>No effects on the memory tasks, MSLT showed ↑ Sleepiness</td>
</tr>
<tr>
<td>Randazzo et al.</td>
<td>(n = 16) 7 m, 9 f 10–14 yrs</td>
<td>Verbal, visual, general memory</td>
<td>PSG, MSLT, battery of performance (WRAML, TTCT, CCT, WCST, CVLT) and sleepiness measures</td>
<td>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).</td>
<td>Sleep restriction: ↑ Latencies in MSLT, verbal creativity (TTCT) and abstract thinking (WCST) were affected, none of the low cognitive load measures were affected</td>
</tr>
<tr>
<td>Sadeh et al.</td>
<td>(n = 77) 39 m, 38 f 9.1–12.2 yrs</td>
<td>Visual memory, working memory</td>
<td>Actigraphy, daily sleep-wake diaries, Neuropsychological Evaluation System (NES)</td>
<td>Days 1 &amp; 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.</td>
<td>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</td>
</tr>
<tr>
<td>Beebe et al.</td>
<td>(n = 64) m, 2 f mean age 15.3 +/- 0.7 years</td>
<td>Attention, working memory</td>
<td>Actigraphy, sleep self reports, parents’ observations, fMRI scans, n-back task paradigm</td>
<td>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</td>
<td>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</td>
</tr>
</tbody>
</table>

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.
Sleepiness, number attempted, word memory

Table 3: Studies with total sleep deprivation.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Methods, measurements</th>
<th>Experimental conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backhaus et al.56</td>
<td>n = 12 males, 18.1 ± 0.2 yrs</td>
<td>Declarative memory consolidation</td>
<td>Experiment 1: sleep condition: learning and first recall at 20:00 h; 2 nights with regular bedtime at home; sleep deprivation condition: 4 different lists of 24 pairs of English–German vocabulary items 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.</td>
<td>Recall of declarative memories was enhanced in children (6–8 years) and adults (Table 4). As in the 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 than non-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.</td>
</tr>
</tbody>
</table>

Further support for decreased implicit performance after sleep in children comes from a study by Backhaus et al.56 This group examined effects of sleep 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.

Neural correlates

Already back in 1988, Horne60 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.56 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.51 This model is consistent with findings by Sadegh et al.51 where sleep restriction led to reduced neurobehavioral functioning compared to equal periods of daytime wakefulness. Consistent with the two-process model of sleep-related memory consolidation,50 declarative memory consolidation specifically benefited from high percentages of NREM sleep (Tables 4 and 5). Wilhem and co-workers57 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.
<table>
<thead>
<tr>
<th>Author</th>
<th>Sample</th>
<th>Memory type</th>
<th>Methods, measurements</th>
<th>Experimental conditions</th>
<th>Results</th>
</tr>
</thead>
</table>
| Gomez et al.54  | n = 48; 8 m, 8 f in each condition 15 months                           | Veridical memory                                 | 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 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 1 on 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.

<table>
<thead>
<tr>
<th>Tests author</th>
<th>Description</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D object location task (OLT) Rasch et al.59</td>
<td>The 2D OLT resembles the game “concentration” and consists of 15 card-pairs showing coloured pictures of different animals and everyday objects; a carded 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 card recall procedure.</td>
<td>Number of correct recalls</td>
</tr>
<tr>
<td>California Verbal Learning Test (CVLT) Delis et al.70</td>
<td>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.</td>
<td>Total score across all trials</td>
</tr>
<tr>
<td>Children’s Category Test (CCT) Boll71</td>
<td>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.</td>
<td>Number of errors</td>
</tr>
<tr>
<td>Finger sequence tapping task Walker, et al.72</td>
<td>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.</td>
<td>Correct sequences, time</td>
</tr>
<tr>
<td>Listening attention task Evans-Pritchard73</td>
<td>The n-back task has been widely used in human neuroimaging and psychophysical studies (e.g., Anourova et al.24); 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.</td>
<td>Percentage of incorrect, missed and multiple responses; reaction time</td>
</tr>
<tr>
<td>Neurobehavioural Evaluation System (NES) Letz74</td>
<td>A test developed to detect variations in neuropsychological functioning; adapted for children (e.g., Dahl et al.50); 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.</td>
<td>Number of taps; reaction time; omission and commission errors; response latency; error score</td>
</tr>
<tr>
<td>Serial alternation task Lubin et al.75</td>
<td>Subjects are instructed to tap 2 switches regularly and alternately at a steady pace for 15 min</td>
<td>Cumulative score of number of sec failed to tap</td>
</tr>
<tr>
<td>Serial digit learning test Letz76</td>
<td>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.</td>
<td>Number of correct recall of sequences</td>
</tr>
<tr>
<td>Serial Reaction Time Task (SRTT) Thomas et al.77; Peigneux et al.78</td>
<td>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.</td>
<td>Number of correct responses, time</td>
</tr>
<tr>
<td>Subtest ‘auditory working memory’ and ‘numbers reversed’ of the Woodcock-Johnson III Tests of Cognitive Abilities Woodcock (WJ III), McGrew &amp; Mather79</td>
<td>‘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.</td>
<td>Test scores</td>
</tr>
<tr>
<td>Symbol Digit Substitution Task (SDS) Letz75</td>
<td>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).</td>
<td>Test scores</td>
</tr>
<tr>
<td>Torrance Tests of Creative Thinking (TTCT) Torrance80</td>
<td>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.</td>
<td>Test scores</td>
</tr>
<tr>
<td>Visual and Verbal Memory test (VVM) Schelleng &amp; Schaechtele81</td>
<td>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.</td>
<td>Test scores</td>
</tr>
</tbody>
</table>
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
Test scores
Number of problems attempted, correct responses
Number of correct recalls

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

Wide Range Assessment of Memory and Learning (WRAML)
Wilkinson Addition Test
Adams & Sheslow
82 Subjects have to add columns of 5 two-digit numbers
Number of problems attempted, correct responses

Williams Word Memory Test
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.
Number of correct recalls

Wisconsin Card Sorting Test (WCST)
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

Word-pair associate learning task
Plihal & Born
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 in 60 s; at retrieval testing after the retention interval, the same cued recall procedure is used with each word-pair tested once.

Abbreviations: yrs, years; h, hours; min, minutes; sec, seconds.
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, 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 and most adolescents sleep less than the recommended time.

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
