Developmental Differences in Sleep's Role for Implicit Off-line Learning: Comparing Children with Adults

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Abstract

■ Sleep crucially contributes to the off-line consolidation of memories. Although this view was confirmed in numerous studies in adults, it is not known whether it can be generalized to sleep during development. Here, we examined effects of sleep on implicit memory formation considered of particular relevance in children, because brain structures underlying implicit learning develop earlier in ontogeny than structures supporting explicit learning. Subjects were 7- to 11-year-old children ($n = 14$) and 20- to 30-year-old adults ($n = 12$) tested on a serial reaction time task before (learning) and after (retest) equal length retention periods of overnight sleep and daytime wakefulness. At learning, after eight training blocks, all subjects had acquired implicit knowledge of the probabilistic rules underlying the sequential stimulus materials, as indicated by a substantial difference in response time to grammatical versus nongrammatical trials in two test blocks that followed the training blocks. At learning, this response time difference was greater in children (48.49 ± 6.08 msec) than adults (28.02 ± 3.65 msec, $p < .01$), but did not differ between sleep and wake retention conditions in either age group. Consistent with previous studies, retesting in the adults revealed that the reaction time differences between grammatical and nongrammatical trials increased by 9.78 ± 4.82 msec after sleep, but decreased by -12.76 ± 5.49 msec after the wake retention period ($p < .01$). Contrary to this finding in adults, sleep in children did not lead to an increase, but to a decrease in the reaction time difference averaging -26.68 ± 12.25 msec ($p < .05$), whereas across the wake retention interval the reaction time difference remained nearly unchanged. The sleep-dependent deterioration in measures of implicit sequence knowledge in children was in striking contrast to the gain of such knowledge in the adults during sleep ($p < .01$). Our findings indicate that the functional role of sleep in implicit memory consolidation depends on age. We speculate that the overnight decrease of implicit knowledge in children reflects a preferential effect of sleep toward the enhancement of explicit aspects of task performance that interferes with implicit performance gains. ■

INTRODUCTION

During the last years, a large number of studies in adult humans has provided compelling evidence that sleep crucially enhances the consolidation of memories (Walker & Stickgold, 2006; Stickgold, 2005; Maquet, 2001). Memory consolidation refers to a process triggered by a learning experience that transforms the newly encoded representations into an enduring form and thereby may not only counteract forgetting but can even improve retrieval (McGaugh, 2000; Müller & Pilzecker, 1900). A supporting role of sleep for memory consolidation has been substantiated for both implicit (or procedural) as well as explicit (or declarative) types of memory (i.e., memory for facts and episodes), although the majority of studies has focused on the former memory system (Gais & Born, 2004; Walker & Stickgold, 2004). "Implicit" refers to a class of memories that,

contrasting with explicit memories, can be acquired unintentionally without any awareness of having acquired or accessed any new information (Schacter & Tulving, 1994; Schacter, 1992; Tulving & Schacter, 1990). Implicit memories are difficult or even impossible to access consciously, and their retrieval is implicit in the sense that it does not rely on conscious recollection, like the recall of explicit memories. Contrasting with explicit memories that can occur after a single exposure to the target stimulus, implicit memories develop only after many stimulus repetitions and extended periods of practice (Karni et al., 1998). Studies in patients with brain lesions and neuroimaging studies have provided support for the notion that implicit memory relies on a dissociable system of brain structures, including primarily cortico-striatal circuitry, whereas explicit memory relies essentially on hippocampal function (e.g., Squire, Stark, & Clark, 2004; Boyd & Winstein, 2001; Reber & Squire, 1998; Grafton, Hazeltine, & Ivry, 1995).

Implicit and explicit memory processes normally closely interact during learning in everyday life (Born

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& Wagner, 2004; Poldrack & Packard, 2003). However, during childhood development, implicit memory formation appears to be of much greater relevance than in adulthood. Several studies provide evidence that the implicit memory system already matures early in infancy and after the age of about 3 years is maintained at a fairly constant level independent of age, whereas explicit learning capacity steadily increases throughout childhood (Murphy, McKone, & Slee, 2003; Vinter & Detable, 2003; Thomas & Nelson, 2001; Meulemans, Van der Linden, & Perruchet, 1998). It has been argued that this well-functioning implicit memory system enables children from an early age on to gradually acquire stimulus regularities contained in sensory and motor inputs and is thereby critical for the child's behavioral, cognitive, and emotional adaptation to environmental constraints (Thomas & Nelson, 2001; Vinter & Perruchet, 2000; Perruchet & Vinter, 1998; Chandler, 1993; Krist, Fieberg, & Wilkening, 1993). In line with this concept, neuroimaging studies show that developmental increases in metabolic rate and myelination of basal ganglia neurons are complete within the first year of life (Chugani, Phelps, & Mazziotta, 1987; Sidman & Rakic, 1982). However, other studies suggest that in structures critical for implicit memory (such as the caudate nucleus and its connections with the prefrontal cortex), maturation continues into adolescence, thus challenging the view of a "developmental invariance" of implicit in contrast with explicit memory (Casey et al., 2004; Olesen et al., 2003; Sowell et al., 1999; Yakovlev & Lecours, 1967). In fact, implicit learning has been revealed to be age-dependent in testing conditions particularly sensitive to a preexisting base of knowledge and strategies (Thomas et al., 2004; Murphy et al., 2003).

The serial reaction time task (SRTT) is a paradigm that has been widely used to assess implicit memory function in adults (Thomas et al., 2004; Peigneux et al., 2003; Thomas & Nelson, 2001; Meulemans et al., 1998; Willingham, Nissen, & Bullemer, 1989; Knopman & Nissen, 1987; Nissen & Bullemer, 1987). 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. Despite remaining unaware of these rules, subjects typically develop implicit knowledge about the spatio-temporal constraints of the underlying structure as a consequence of prolonged training. This is reflected by increased response times to sudden violations of the rules. Several studies demonstrated that the SRTT is also an appropriate tool for investigating implicit learning in children. Using a deterministic grammar, Meulemans et al. (1998) compared SRTT performance between children aged

6 to 7 years, children aged 10 to 11 years, and adults. Although response times generally decreased with age, implicit learning, measured as the difference in response time to a structured sequence as compared with a random sequence of the target stimulus, was closely comparable in the three groups. This finding indicating that young children can implicitly acquire the structure of the sequence as well as adults, has been subsequently confirmed in another study in children down to 4 years (Thomas & Nelson, 2001). However, a recent functional magnetic resonance study of the same group indicated a smaller sequence learning effect in 7- to 11-year-old children than in adults, which was associated with a differential recruitment of task-related brain structures (Thomas et al., 2004).

In adults, the formation of lasting memories for skills as required by the SRTT depends essentially on sleep (Peigneux et al., 2003; Walker, Brakefield, Hobson, & Stickgold, 2003; Fischer, Hallschmid, Elsner, & Born, 2002; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). If in these studies training was followed by a period of sleep, skill performance at a later retrieval testing was distinctly enhanced to levels above those reached at the end of the training session. Thus, aside from an improvement during practice, training a skill apparently triggers a latent off-line learning process that continues after practice has ended and is crucially enhanced by sleep leading to a gain of skill at later retesting (Walker & Stickgold, 2006; Stickgold, 2005). Regarding the SRTT, it has been demonstrated in adults that sleep strengthens implicit learning of a probabilistic grammar underlying the sequence of target positions, as indicated by an increased difference between response times to grammatical and nongrammatical trials (Peigneux et al., 2003). This effect of sleep was accompanied by a general decrease in response times. Interestingly, brain regions involved during learning the SRTT were reactivated during subsequent rapid eye movement (REM) sleep, with the strength of reactivation (as assessed by positron emission tomography) being correlated to the level of acquisition of the rules underlying the sequence (Peigneux et al., 2003; Maquet et al., 2000). Other neuroimaging studies likewise indicate that sleep-dependent motor skill learning is associated with a distinct reorganization of the brain representation of the skill, suggesting sleep facilitates plastic brain processes underlying memory formation (Fischer, Nitschke, Melchert, Erdmann, & Born, 2005; Walker, Stickgold, Alsop, Gaab, & Schlaug, 2005; Maquet, Schwartz, Passingham, & Frith, 2003).

Although these studies underline a critical role of sleep for the implicit learning of skills in adults, there is a paucity of studies investigating whether sleep contributes similarly to learning in development in children. One recent study by Gómez, Bootzin, and Nadel (2006) in 15-month-old infants examined influences of naps in an artificial language learning task. Compared with nonnapping controls, infants who had napped in the

retention interval between learning and retrieval showed signs of a diminished memory for the language features learned before, but appeared to have abstracted, to a greater extent then the controls, a rulelike pattern from the stimulus materials. Investigating song learning in developing birds (zebra finch), Deregnaucourt, Mitra, Feher, Pytte, and Tchernichovski (2005) likewise observed a deterioration in song structure after nocturnal sleep. However, song structure recovered strongly during daytime, and birds that showed stronger postsleep deterioration eventually achieved a better final imitation of the song. Adult animals did not show a postsleep deterioration of the trained song. These findings suggest that sleep also enhances plastic processes underlying learning in development, although this influence, contrasting with memory formation in adults, may manifest itself in an acute deterioration of the trained skill after sleep. Here, we aimed at probing the role of sleep for learning in development in children. For this purpose, the implicit learning performance on an SRTT was tested in 7- to 11-year-old children and in adult controls before and after retention periods of equal duration covering either nocturnal sleep or daytime wakefulness. Learning before sleep consisted of eight training blocks followed by two test blocks in which occasionally nongrammatical target positions occurred. At retesting after the retention period, after a short warming up, the subjects again performed on the two test blocks. Based on the available data, we expected that although overall response times are slower in children than adults, both groups would show a gradual increase in speed during initial SRTT training. The central hypotheses regarding performance on the SRTT test blocks were the following: (a) At learning before the retention interval, both groups show measures of implicit knowledge in terms of a significant difference between reaction times to grammatical and nongrammatical trials, which should be roughly comparable between the groups. (b) Compared with wakefulness, sleep during the retention interval leads to a distinct increase in response time differences (i.e., increased implicit sequence knowledge at retesting). Considering children's sleep is deeper, this increase could be even more pronounced in the children than in the adults.

METHODS

Subjects

Fourteen children between the age of 7 and 11 years (mean age ± SD: 9.42 ± 1.38 years; seven girls and seven boys) were recruited for this study. All children went to the same elementary school near the sleep laboratory and were asked by their teachers if they wished to participate in the study. The children were of normal intelligence, had no school problems, and were healthy as assured by a routine pediatric examination. We carefully surveyed the children's sleep schedules by a parent interview and designed the study such that bedtime in the experimental sleep condition matched well with the time the children normally slept at home (i.e., from ~10:00 p.m. to ~7:00 a.m. the next morning). Habitual sleep time according to the parents' report averaged (mean ± SEM) 9.47 ± 0.23 hr. None of the children were used to taking naps during the day. Data from one girl who did not finish the experimental task were not included in the analysis. The group of adult participants consisted of 12 healthy volunteers aged between 20 and 30 years (mean age ± SD: 24.25 ± 3.08 years; four women and eight men). The subjects were adjusted to the sleep laboratory by an adaptation night, which took place before the experiment proper, but not on the night immediately preceding the experimental night. Subjects in both groups were right-handed and had regular sleep schedules during the 6 weeks before the study. None of them took any medication or had a history of neurological or psychiatric disorders. Subjects were not allowed to nap during the day or to drink any alcoholic or caffeine-containing drinks on the days of the experiment. Before study participation, written informed consent was obtained from all subjects, according to the ethics committee of the University of Lübeck. For the children, this was accomplished by a parent. In addition, all children provided verbal assent to participate.

Design and Procedure

Each subject participated in two conditions, a "sleep" and a "wake" condition separated by an interval of at least 4 weeks. The order of conditions was balanced across subjects. In each condition, implicit learning on a SRTT was assessed before (learning) and after (retest) a retention interval of about 11 hr that included overnight sleep or a period of daytime wakefulness (Figure 1A).

In the sleep condition, subjects reported to the sleep laboratory in the evening and were first prepared for polysomnographic recordings. Initial learning on the SRTT (including training and test blocks of the task) started at approximately 8:00 p.m. in the children and at approximately 9:00 p.m. in the adults and lasted for about 60 min. The children went to bed at 10:00 p.m. and the adults at 11:00 p.m. At this time, lights were turned off, and polysomnographical recordings started. All subjects were awakened at 7:00 a.m. the next morning, and retesting on the SRTT started 30 min later. In the wake condition, initial learning on the SRTT took place at approximately 8:00 a.m. in the children and at approximately 9:00 a.m. in the adults. Retesting began at approximately 7:30 p.m. To adjust the time schedule to the individual habitual sleep time, in the children, the actual times of testing could differ from these times by up to 30 min. In the end of each experimental session, subjects were asked to estimate their subjective feelings

Figure 1. Study design, SRTT, and an example sequence of target locations. (A) In the sleep condition, the SRTT was performed in the evening before a night of regular sleep (learning) and retesting (retest) took place in the next morning. Subjects were awakened 30 min before retesting. In the wake condition, the SRTT was performed in the morning (learning) and in the evening (retest) of the same day, with subjects staying awake during the retention interval between learning and retesting. The retention interval covered a period of approximately 11 hours in both conditions. (B) On the SRTT, subjects were presented with six horizontally arranged white boxes. The target cue consisted of a white star that successively appeared in the center of one of the boxes. The subject was asked to react as fast and as accurately as possible on each trial by pressing the spatially corresponding response key,

as soon as the cue was presented. (C) The sequence of target locations in the SRTT was based upon a set of probabilistic rules such that each of two successive trials constituted the temporal context that legally could be followed by one of two possible target locations, each occurring with a probability of 50%. In the illustrated example sequence, the temporal context "D," "A" (gray fields) could be legally followed by position "C" or "F."
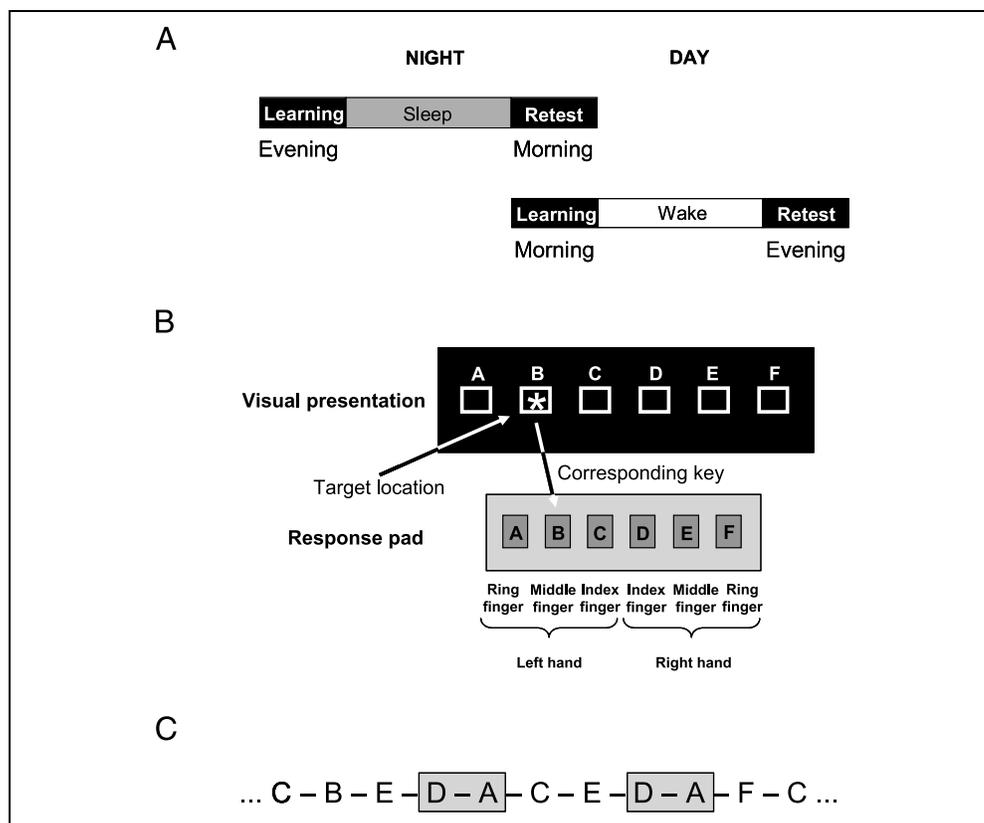
Learning Task

An SRTT was used to assess implicit learning. Subjects were informed that the task assessed vigilance. During task performance subjects sat in a reclining chair in a darkened and silent room in front of a 17-in. computer monitor. On the screen, six horizontally arranged white boxes were permanently presented against a black background (Figure 1B). Each of these screen positions corresponded to one of six response keys placed in front of the subject. Subjects were instructed to place the index, middle, and ring fingers of the left hand on the left three response keys and those of the right hand on the right three response keys. The target cue consisted of a white star that successively appeared in the center of one of the boxes. The subject was asked to react as fast and as accurately as possible on each trial by pressing the spatially corresponding response key, as soon as the cue was presented. Each cue remained on the computer screen until the subject responded. Incorrect responses

were indicated by a short beep. No feedback was given for correct responses. The next target cue was displayed after a fixed interval of 120 msec after the subjects' response. Target cues were presented in blocks of 194 trials, separated by breaks, the duration of which were determined by the subject, but never exceeded 3 min. The children were allowed to take extra breaks within a block, which, however, never happened.

Unknown to the subjects, the transitions of the target cue from one screen position to another did not occur at random, but was based on a probabilistic finite state grammar (i.e., a set of rules defining the legal transitions between successive trials). According to this grammar, each of two successive target positions, in principle, could be followed by two possible target positions, each occurring with a probability of 50% (Table 1). For example, the successive occurrence of the target cue at positions "D" and "A" could be legally followed only by position "C" or "F" (Figure 1C). By this means, the grammar defined a spatio-temporal context of second order in which each target position occurred. Immediate repetitions as well as alternations were not possible. Each single target position and each spatio-temporal context occurred with the same frequency in a block. To allow testing of the same subject in both the sleep

of tiredness, activation, and concentration. In the adults, this was done using a standardized checklist (Janke & Debus, 1978). Children were given a semistructured interview by the experimenter.

Table 1. Probabilistic Rules Underlying the Sequence of Target Cues

	A	B	C	D	E	F
AC	0	0	0	0	.5	.5
AD	0	0	.5	0	0	.5
AE	0	0	.5	.5	0	0
AF	0	0	.5	.5	0	0
BD	.5	0	0	0	0	.5
BE	.5	0	0	.5	0	0
BF	0	0	0	.5	.5	0
BA	0	0	0	.5	.5	0
CE	.5	.5	0	0	0	0
CF	0	.5	0	0	.5	0
CA	0	0	0	0	.5	.5
CB	0	0	0	0	.5	.5
DF	0	.5	.5	0	0	0
DA	0	0	.5	0	0	.5
DB	.5	0	0	0	0	.5
DC	.5	0	0	0	0	.5
EA	0	0	.5	.5	0	0
EB	.5	0	0	.5	0	0
EC	.5	.5	0	0	0	0
ED	.5	.5	0	0	0	0
FB	0	0	0	.5	.5	0
FC	0	.5	0	0	.5	0
FD	0	.5	.5	0	0	0
FE	0	.5	.5	0	0	0

The first column indicates the target positions of two successive trials (e.g., ''D,'' ''A'') that constitute the temporal context that can be legally followed by one of two possible target positions. The next six columns indicate the probability of each of the six target positions to succeed this temporal context (''D,'' ''A'' could be legally followed by position ''C'' and ''F'' each occurring with a probability of 50%).

and wake conditions, two parallel forms of the task were created, each by randomly mapping the grammar labels (''A,'' ''B,'' ''C,'' etc. as illustrated in Figure 1B) onto the different target positions on the computer screen. Within each of the two forms of the task this mapping was held constant across subjects. However, to control for motor effects and serial order effects, the mapping of each grammar label on its actual screen position was systematically shifted one step to the right per subject. Learning before the retention interval included a training phase consisting of eight blocks of the SRTT. Immediately after training, two test blocks were presented to probe implicit learning of the hidden rules. For this

purpose, 15% of the grammatical target locations were replaced by noncorrect locations violating the rules of the underlying grammar. Nongrammatical trials exclusively violated second-order contingencies. They also never led to alternations in the sequence and equally often occurred at each of the six screen positions. The amount of implicit learning of the grammar was then determined by calculating the difference between response times to nongrammatical versus grammatical target location in the two test blocks.

At retesting after the retention interval, subjects first performed on two regular SRTT blocks containing only grammatical stimulus transitions. The blocks served as warm-up phase and did not enter analysis. Thereafter, they performed again on two test blocks each containing 15% nongrammatical trials.

Dependent Variables and Statistical Analyses

Individual SRTT performance on the training blocks and the test blocks was determined by calculating the median reaction times for all correct responses per block. For the test blocks performed at learning before and at retesting after the retention interval, this was done separately for grammatical and nongrammatical trials. Implicit learning of the sequential constraints set by the grammar was expressed in term of the difference between the average reaction time to grammatical and nongrammatical trials. Grand means were formed across subjects in each group.

Sleep was assessed by standard polysomnography. Recordings were visually scored off-line according to the criteria of Rechtschaffen and Kales (1967) by two independent experimenters. For each night, time (in minutes) spent in the different sleep stages (wake, Stages 1–4 sleep, REM sleep) was determined and transformed into percentages of total sleep time (TST). Time in slow-wave sleep (SWS) was defined by the sum of Stages 3 and 4 sleep. Sleep onset latency (i.e., the first occurrence of a period of Stage 1 sleep followed by Stage 2 sleep) was determined with reference to the time of lights off. Latencies of SWS and REM sleep were determined with reference to sleep onset.

Statistical analysis of reaction times was performed separately for the training and test blocks. It was based on analyses of variance (ANOVA), including generally one between-subject factor (adults vs. children) and the within-subject factor (sleep/wake) and, for the test blocks, additionally two within-subject factors (learning/ retesting and grammatical/nongrammatical). Effects including the grammatical/nongrammatical factor were specified in ANOVA on the differences in response times to the two types of trials. Post hoc comparisons were performed, using F tests for paired and unpaired measures, respectively. Sleep parameters were analyzed using (unpaired) Student's t tests. In explorative analyses, sleep parameters were correlated with overnight

Table 2. Reaction Times on the SRTT Test Blocks

SRTT Test Blocks	Children		Adults	
	Wake	Sleep	Wake	Sleep
Learning				
Grammatical	726.99 ± 52.68	676.40 ± 25.38	495.46 ± 18.30	486.35 ± 25.43
Nongrammatical	770.40 ± 54.62***	729.98 ± 25.04***	523.78 ± 19.31***	514.06 ± 25.67***
Difference	43.41 ± 12.43	53.57 ± 10.35	28.32 ± 6.05	27.71 ± 1.51
Retest				
Grammatical	667.72 ± 41.09	652.59 ± 22.73	475.92 ± 19.76	471.25 ± 24.46
Nongrammatical	718.66 ± 45.57***	679.49 ± 20.69***	491.49 ± 21.91***	508.74 ± 25.36***
Difference	50.94 ± 11.24	26.89 ± 6.71**	15.56 ± 3.64**	37.49 ± 5.50**·*

Values are means ± *SEM* (msec).

Significant pairwise comparisons with reference to ***grammatical target locations ($p < .005$ for all comparisons), **performance at learning ($p < .05$, except for the sleep condition in adults where $p < .07$), and *performance in the wake condition ($p < .01$).

changes in SRTT performance using Pearson's correlation coefficients.

RESULTS

Comparison of Serial Reaction Time Task Performance between Children and Adults

During initial training, response times were clearly longer in the children than adults [children: 717.90 ± 30.95 msec; adults: 497.19 ± 16.79 msec; $F(1,23) = 37.51$, $p < .001$; Figure 2]. On the other side, children showed greater improvements in speed during training (13.52 ± 3.55 msec per block) than adult subjects [5.34 ± 0.87 msec per block; $F(1,23) = 7.48$, $p < .01$], although this did not hold for percent transformed improvements [children: 11.47 ± 2.78%; adults: 7.77 ± 1.14%; $F(1,23) = 1.96$, $p > .2$].

Global ANOVA on response times during the two test blocks before and after the retention intervals revealed a main effect adults/children indicating that response times (across grammatical and nongrammatical trials) were slower in the children than in the adults [702.78 ± 13.58 msec vs. 495.89 ± 7.93 msec, $F(1,23) = 30.60$, $p < .001$]. As expected, a highly significant main effect of grammatical/nongrammatical [$F(1,23) = 151.01$, $p < .001$] indicated distinctly faster responses to grammatical than to nongrammatical trials. Because the grammatical/nongrammatical factor, in addition contributed to several significant interaction terms, we proceeded with a global ANOVA performed directly on response time differences between grammatical and nongrammatical trials. Importantly, in this analysis, the 3-way Children/Adult × Sleep/Wake × Learning/Retesting interaction reached significance [$F(1,23) = 4.56$, $p < .05$], indicating a differential effect of sleep versus wakefulness in chil-

dren and adults on response time differences between grammatical and nongrammatical trials before and after the retention interval. To explore the possibility that this interaction effect arose mainly based on the obvious baseline differences in reaction times between age groups, we repeated the analysis after z-transforming the data with reference to global response times at learning, thereby removing group differences in absolute reaction times. This ANOVA on the normalized data confirmed significance for the Children/Adult × Sleep/Wake × Learning/Retesting interaction [$F(1,23) = 6.79$, $p < .01$]. We further specified the 3-way interaction in separate analyses on the data from learning and retesting and from the sleep and wake conditions. The analyses revealed that at learning before the retention interval, implicit learning in terms of response time differences between grammatical and nongrammatical trials was greater in the children than adult subjects [$F(1,23) = 8.00$, $p < .01$], which might partly reflect the generally slower response speed in the children. The most striking result, however, was obtained in the analysis of the sleep condition indicating that sleep influenced the response difference between grammatical and nongrammatical trials (i.e., implicit off-line learning) in children and adults in opposite directions. Although retention sleep in the adults caused a gain in implicit learning (i.e., greater response difference between grammatical and nongrammatical trials at retesting with reference to performance at learning), in the children, this measure of implicit learning was clearly weakened after retention sleep [$F(1,23) = 7.21$, $p < .01$, for Children/Adult × Learning/Retesting; see Figure 3 also for results from post hoc pairwise comparisons]. In separate analyses on the wake conditions, the same Children/Adult × Learning/Retesting interaction term remained without

significance [$F_{(1,23)} = 1.30$, $p > .27$] excluding a substantial contribution of the wake retention interval to the differential dynamics of implicit learning observed in both groups. We subsequently performed detailed analyses separately on the data from the children and adults.

Serial Reaction Time Task Performance in Children

During initial training, performance speed in the children gradually improved from the first to the last block of training on average by 11.47% ± 2.78% [$F_{(1,12)} = 23.38$, $p < .001$]. Overall, the improvement appeared to be somewhat smaller during the training in the evening than in the morning, although this difference did not reach significance [$F_{(1,12)} = 0.59$, $p > .4$; Figure 2]. Assessed separately, in the evening (sleep condition) response times decreased from 717.02 ± 33.31 msec in Block 1 to 655.31 ± 21.83 msec in Block 8 [percent gain: 6.77 ± 4.34%; gain per block: 7.71 ± 4.36 msec, $F_{(1,12)} = 3.13$, $p < .10$]. In the morning (wake condition) the response times during training decreased from 819.03 ± 77.55 msec in Block 1 to 664.40 ± 48.14 msec in Block 8 [percent gain: 16.17% ± 3.10%; gain per
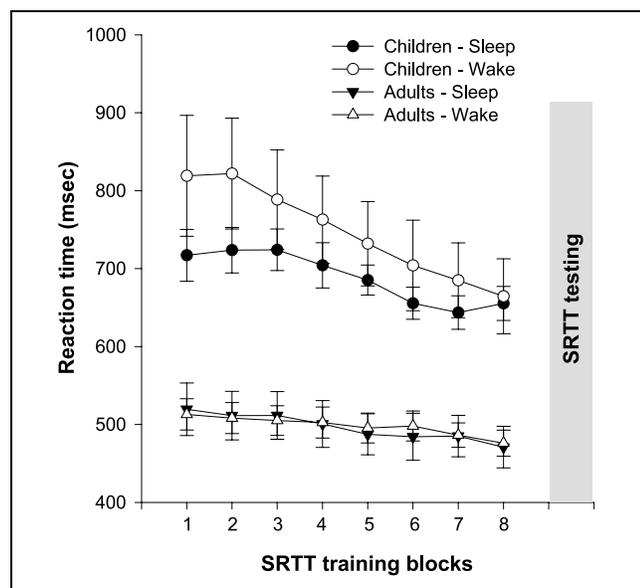

Figure 2. SRTT training before the retention interval. Performance is indicated in terms of mean reaction time (± *SEM*) in the children and adults for the sleep and wake conditions, respectively. SRTT training consisted of eight blocks of 194 trials each. The blocks contained only grammatical trials. As expected, reaction times in adults were faster than in children ($p < .001$). In contrast, reaction time improvements across training were greater in children than in adults ($p < .02$). Within the children group, these improvements appeared to be somewhat smaller in the sleep than in the wake condition, although this difference did not reach statistical significance. Training was followed by two SRTT test blocks containing nongrammatical trials to probe implicit knowledge of the hidden rules underlying the target sequence (Figure 3).

block: 19.33 ± 5.29 msec, $F_{(1,12)} = 13.34$, $p < .003$]. The time course of reaction times across the training blocks was similar between both sleep and wake conditions ($p > .30$, in comparisons performed separately for each of the eight blocks).

After the training, when nongrammatical trials were introduced in the test blocks of the learning phase, response times (for the grammatical trials) slightly increased from 655.31 ± 21.83 (last block of training) to 676.40 ± 25.38 msec in the sleep condition and from 664.40 ± 48.14 to 726.99 ± 52.68 msec in the wake condition [$F_{(1,12)} = 31.42$, $p < .001$, across the sleep and wake conditions]. In addition, this increase was on average greater in the daytime wake than nocturnal sleep condition [$F_{(1,12)} = 7.79$, $p < .05$]. Reaction times to grammatical trials during the two test blocks did not differ between the sleep and wake conditions [$F_{(1,12)} = 1.00$, $p > .3$].

Mean response times in the test blocks of the SRTT presented before and after the retention interval are summarized in Table 2 (left). ANOVA revealed a significant learning/retest main effect indicating that the children were generally (i.e., to grammatical and nongrammatical trials) faster on the two test blocks at retesting after the retention interval than in the test blocks of the learning phase [$F_{(1,12)} = 28.16$, $p < .001$]. This general improvement in speed averaged 5.08% ± 1.25% in the sleep condition [$F_{(1,12)} = 15.77$, $p < .002$] and 6.52% ± 1.66% in the wake condition [$F_{(1,12)} = 12.85$, $p < .005$] and did not differ between the conditions [$F_{(1,12)} = 0.96$, $p > .3$]. As expected, in the children response times were slower to nongrammatical than to grammatical trials [$F_{(1,12)} = 39.07$, $p < .001$, grammatical/nongrammatical main effect] with this effect being significant in both the sleep [$F_{(1,12)} = 16.05$, $p < .002$] and the wake condition [$F_{(1,12)} = 20.51$, $p < .001$]. This held also true for a separate analysis of the test blocks at learning before the retention interval [$F_{(1,12)} = 63.69$, $p < .001$] in the sleep condition [$F_{(1,12)} = 26.76$, $p < .001$] as well as in the wake condition [$F_{(1,12)} = 12.19$, $p < .004$; Figure 3], indicating that at learning children in both conditions had acquired implicit knowledge of the rules underlying the sequential task. Importantly, differences in response times to grammatical and nongrammatical trials in these two test blocks serving as baseline were closely comparable between the sleep and wake conditions [$F_{(1,12)} = 0.28$, $p > .6$]. Interestingly, however, contrary to our expectation, the differences in reaction times between grammatical and nongrammatical trials did not increase but distinctly decreased across nocturnal sleep. This decrease reflecting weakened implicit sequence knowledge averaged 26.68 ± 12.25 msec, corresponding to 64.91% ± 20.64% [$F_{(1,12)} = 4.74$, $p < .05$; $F_{(1,12)} = 2.00$, $p < .1$, for respective Sleep/ Wake × Learning/Retesting interaction in an analysis on response time differences]. In the wake condition, reaction time differences between grammatical and non-
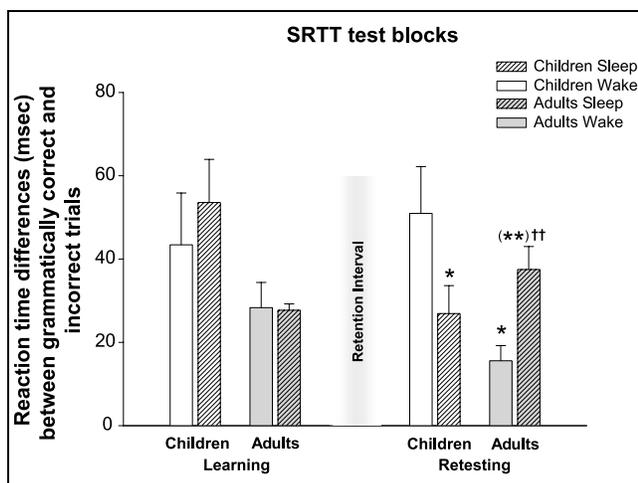
Figure 3. SRTT testing before and after retention intervals of sleep and wakefulness in the children and adults. During SRTT testing, subjects performed two blocks of 194 trials, each containing 15% nongrammatical target positions. Bars, as a measure of implicit knowledge of the grammar underlying the target sequence, represent mean reaction time differences between grammatical and nongrammatical trials. With reference to the learning period, in children, sleep during the retention interval led to a decrease in the reaction time difference (i.e., to decreased implicit sequence knowledge) at retesting, whereas in adults sleep improved measures of sequence knowledge. The wake retention interval did not affect implicit sequence knowledge in the children, but in adults led to a distinctly diminished sequence knowledge at retesting. *$p < .05$, **$p < .07$, compared with performance at learning; ††$p < .01$, compared with the wake condition.

grammatical trials at retesting were more variable than in the sleep condition, but, on average, were closely comparable to those at learning, showing a negligible increase of 7.53 ± 16.28 msec ($1.27\% \pm 55.21\%$) at retesting after the wake retention period [$F(1,12) = 0.21, p > .6$]. Probably because of the greater variability in the wake condition, differences in this measure at retesting between the wake and sleep conditions failed to reach significance [$F(1,12) = 2.00, p > .2$]. Because error rates remained very low (<5%), they were not subjected to further analyses.

Serial Reaction Time Task Performance in Adults

Comparing performance speed between the first and last block of training, the adults improved on average by $7.77\% \pm 1.14\%$ [$F(1,11) = 56.83, p < .001$], with this gain being similar in the sleep and wake conditions [$F(1,11) = 0.50, p > .5$; sleep condition: first block: 519.41 ± 33.70 msec, last block: 470.95 ± 26.69 msec, corresponding to a gain of $8.66\% \pm 1.50\%$ or 6.06 ± 1.23 msec per block; $F(1,11) = 24.33, p < .001$; wake condition: first block: 512.93 ± 20.09 msec, last block: 476.00 ± 16.76 msec, corresponding to a gain of $6.88\% \pm 1.75\%$ or 4.62 ± 1.26 msec per block; $F(1,11) = 13.45, p < .004$; Figure 2]. There were also no

differences in reaction times for single blocks between both conditions ($p > .71$, for all comparisons). Introduction of nongrammatical trials in the test blocks after training, as in the children, increased response times to the correct trials [sleep: from 470.95 ± 26.69 to 486.35 ± 25.44 msec; $F(1,11) = 9.53, p < .01$; wake: from 476.00 ± 16.76 to 495.46 ± 18.31 msec, $F(1,11) = 15.51, p < .005$], and this increase did not differ between sleep and wake conditions [$F(1,11) = 0.28, p > .6$].

Table 2 (right) summarizes reaction times before and after the retention intervals in both conditions. ANOVA revealed a significant "learning/retest" main effect indicating that the adults, like the children, had generally faster response times at retesting after the retention interval with the decrease in response times averaging $3.56\% \pm 0.97\%$ [$F(1,11) = 9.98, p < .01$]. As expected, response times were slower to nongrammatical than to grammatical trials [$F(1,11) = 71.52, p < .001$, grammatical/nongrammatical main effect] in both the sleep [$F(1,11) = 46.36, p < .001$] and the wake conditions [$F(1,11) = 18.26, p < .001$]. This difference in response time between grammatical and nongrammatical response times was also obvious in a separate analysis of the test blocks at learning before the retention interval [$F(1,11) = 58.97, p < .001$] in both the sleep [$F(1,11) = 334.07, p < .001$] and wake conditions [$F(1,11) = 21.87, p < .001; F(1,11) = 0.02, p > .9$, for the comparison between conditions], thus confirming that training resulted in implicit sequence knowledge that was comparable in both conditions. However, across the retention interval, the response time difference showed the expected differential change depending on whether subjects slept or stayed awake during the retention interval [$F(1,11) = 18.26, p < .01$, for Sleep/Wake × Learning/Retesting; Figure 3]. Whereas the response time differences on average decreased by $43.73\% \pm 29.30\%$ in the wake condition [$F(1,11) = 5.41, p < .05$], sleep led to an increase of $33.80\% \pm 16.33\%$ in this performance measure [$F(1,11) = 4.13, p < .07$]. Consequently, the difference between grammatical and nongrammatical trials at retesting after the retention interval differed markedly between the wake and the sleep conditions [$F(1,11) = 10.06, p < .01$]. The adults' error rate was like the children's also very low (<4%) and not further analyzed.

Sleep

Children overall slept distinctly better than adults (see Table 3, for a summary of results). Compared with the adults, our children slept longer ($t = -3.36, p < .005$), showed a shorter SWS latency (with reference to sleep onset, $t = 3.69, p < .005$), and a longer REM sleep latency ($t = -3.56, p < .005$). Moreover, the children spent less time in the lighter Stages 1 and 2 sleep (for percent values, $t = 2.18, p < .05$, and $t = 2.61, p < .01$, respectively), but showed distinctly greater amounts of SWS ($t = -4.36, p < .005$).

Table 3. Sleep Parameters

Parameters	Children	Adults
Total sleep time, min	498.83 ± 7.32	460.93 ± 8.35*
Sleep onset, min	12.08 ± 1.67	16.18 ± 8.24
SWS latency, min	10.83 ± 1.11	18.12 ± 1.75*
REM latency, min	168.75 ± 15.51	88.93 ± 14.43*
Wake time, min (%)	16.66 ± 9.29 (3.33 ± 1.85)	9.54 ± 0.89 (2.07 ± 0.18)
Stage 1 sleep, min (%)	23.49 ± 5.67 (4.71 ± 1.07)	38.07 ± 6.02 (8.26 ± 1.24)**
Stage 2 sleep, min (%)	219.98 ± 15.42 (44.1 ± 3.46)	254.53 ± 8.98 (55.22 ± 2.34)**
SWS, min (%)	144.04 ± 14.89 (29.0 ± 2.65)	68.49 ± 8.62 (14.86 ± 1.77)*
REM sleep, min (%)	92.93 ± 8.73 (18.63 ± 1.66)	89.25 ± 4.43 (19.35 ± 0.85)

Sleep during the nocturnal retention intervals in the children and adults. Mean (±*SEM*) total sleep time, time to sleep onset (after lights off), latency of first period of SWS and REM sleep (with reference to sleep onset), and time spent awake, in Stage 1 sleep, Stage 2 sleep, SWS, and REM sleep (in minutes and percent of total sleep time), for pairwise comparison between groups.

*$p < .005$.

**$p < .05$.

For exploratory purposes, product–moment correlations were calculated between the time spent in specific sleep stages and changes in measures of implicit learning across retention sleep, separately in the groups of children and adults. However, these analyses did not reveal any consistent associations ($r < 0.35, p > .27; r < 0.31, p > .45$, for all comparisons in the children and adult group, respectively). Subjective feelings of activation, tiredness, and concentration assessed at the end of learning and retesting also did not indicate any difference between the sleep and the wake condition neither in the adults nor in the children ($p > .4$, for all comparison, because this assessment was based on different methods in the adults and children, a comparison between both groups was not performed).

DISCUSSION

Our data show that sleep exerts opposite effects on measures of implicit memory consolidation in children as compared to adult subjects. In adults, as expected, the differences between response times to grammatical and nongrammatical target positions (i.e., the major indicator of implicit learning of the SRTT sequence structure) was enhanced after a retention interval of nocturnal sleep, in comparison with a retention interval of daytime wakefulness. Contrary to our expectations inferred from adult studies, in children, retention sleep clearly deteriorated implicit knowledge of the sequence structure, as indicated by reduced reaction time difference to grammatical versus nongrammatical targets at retesting in comparison with levels at learning. The sleep-associated weakening of implicit sequence knowledge emerged on a background of generally slower response times and a distinctly deeper sleep during the retention period in the children than in the adults. Our observations indicate that sleep plays a differential role for processes of implicit off-line learning during childhood development compared with adulthood.

Data of the training period indicated that after the same amount of practice as in adults, our 7- to 11-year-old children became sensitive to the hidden probabilistic structure underlying the succession of target positions in the SRTT. This finding replicates findings of a large number of previous studies, indicating that implicit learning functions are well developed in children from an early age on (e.g., Murphy et al., 2003; Vinter & Perruchet, 2000; Meulemans et al., 1998; Perez, Peynircioglu, & Blaxton, 1998; Perruchet, Frazier, & Lautrey, 1995). Although overall response times to target stimuli were slower in children than in adult subjects, training-related performance gains were even larger, and implicit skill knowledge at posttraining SRTT testing was even more pronounced in our children than in the adult subjects. That these differences in initial learning of the task contributed to our findings at retesting cannot be entirely ruled out, although they cannot account for the opposite directions of the effects of sleep on implicit memory formation present in both age groups. The superior measures of implicit learning in our children diverges from previous studies, most of them indicating that implicit memory is stable across a wide age range (3 years to adulthood) (Pacton, Fayol, & Perruchet, 2005; Murphy et al., 2003; Thomas & Nelson, 2001; Vinter & Perruchet, 2000; Meulemans et al., 1998). Using a similar SRTT in children of similar age, Thomas et al. (2004) even observed a reduced rather than increased

rate of implicit learning in comparison with the adults. The reasons for this discrepancy remain unclear. SRTT training in our study was about twice as long as in Thomas et al.'s study, which might have allowed the children to gain additional implicit sequence knowledge during a period when adults' performance has reached an already asymptotic level. Also, in Thomas et al.'s study, the SRTT was performed in a magnetic resonance imaging scanner that, overall, could have been more distracting to the children than adults. There are also hints that implicit learning in children can be quite sensitive to contextual factors such as the adopted strategy of processing and the knowledge base used (Murphy et al., 2003; Perruchet et al., 1995), and these factors might have also differed between the present and previous studies. Whatever the reasons for the discrepancy, the superiority of our children in comparison with the adults per se remains basically difficult to interpret on the background that overall their reaction times during learning were distinctly slower than in adults. The finding, in any case, seems to be in line with the developmental invariance model, inasmuch as the model proposes an age-associated increase in memory abilities selectively for explicit and not for implicit learning function (Reber, 1993).

Because we examined sleep-dependent off-line learning overnight, although respective intervals of wakefulness were placed during daytime, circadian factors might have confounded our results. However, initial performance in the SRTT in both children and adults was closely comparable regardless of whether training took place in the evening (sleep condition) or in the morning (wake condition). In addition, self-report measurements did not provide any hints toward differences in feelings of activation, concentration, and tiredness at the time of learning or retesting, in both groups. Several previous studies likewise indicated that SRTT performance and related off-line learning do not depend on whether examined during daytime or overnight (e.g., Cohen, Pascual-Leone, Press, & Robertson, 2005; Robertson, Press, & Pascual-Leone, 2005; Robertson, Pascual-Leone, & Press, 2004). Even if response times were differentially influenced by circadian factors, this would be equally true for both grammatical and nongrammatical trials, leaving the difference in response times between grammatical and nongrammatical target positions (i.e., the measure of implicit learning) unaffected.

Our findings in adult subjects replicate previous studies providing evidence that sleep exerts an enhancing effect on implicit off-line learning (Peigneux et al., 2003; Walker et al., 2003, 2002; Fischer et al., 2002, 2005). Although implicit memory for the sequence constraints decreased across the wake retention period, it was increased after a night of sleep, suggesting dual action of sleep, that is, a stabilizing action that counteracts the wake-associated deterioration of implicit memory and an enhancing action leading to a consistent gain of skill

at later retesting (Stickgold, 2005; Walker, 2005). The stabilizing effect of sleep on memories may partly derive from protecting newly acquired representations from unspecific interference (Wixted, 2004). In contrast to memory stabilization, the memory enhancement has been considered to be unique to sleep and to rely on a covert reprocessing of the fresh memories during sleep (Fischer et al., 2005; Walker et al., 2005; Maquet et al., 2000). Data from functional magnetic resonance imaging studies provided evidence that sleep, in conjunction with enhancing performance on procedural tasks, leads to a systematic reorganization of the respective neural representations, that eventually could ease its accessibility (Fischer et al., 2005; Walker et al., 2005; Wagner, Gais, Haider, Verleger, & Born, 2004). The sleep-associated reprocessing and reorganization of memories presumably takes place only within a limited time, because sleep on the first night after training produces the strongest performance improvement (Fischer et al., 2002; Walker et al., 2002). Interestingly, recent studies suggest that the sleep-dependent improvements in an implicit or procedural skill require also some degree of "intentionality" at learning (e.g., regarding certain movement goals), although not an awareness of the truly implicit aspects of the task (Born & Wagner, 2004; Robertson, 2004; Robertson et al., 2004).

Our findings in children stand in striking contrast to those in adults, with implicit memory for the SRTT sequence after sleep being clearly weakened rather than strengthened, as in the adults. Unspecific factors, like tiredness, reduced arousal, or sleep inertia at retesting would not likely explain this outcome. Interviews did not reveal any differences in reported feelings of fatigue or concentration in the children during the sleep and wake conditions, although the general level of subjective activation cannot be compared between the age groups, here, because of different methods of assessment used in the two groups. Previous studies indicated that blood concentrations of cortisol, a hormonal indicator of arousal that might also affect memory retrieval, do not differ after morning awakening between children and adult subjects (Pruessner et al., 1997). Also, we tested children and adults during roughly corresponding times of their habitual sleep–wake cycle to prevent that fatigue at testing from confounding selectively one of the groups. Still, it might be reasoned that the children, although in bed an hour longer than the adults on experimental nights, had not sufficient sleep. Parents' reports indicated that habitual sleep time was about 9.5 hr, which was slightly longer than the average of 8.3 hr the children slept on experimental nights. In addition, most norms in the age group suggest that 9 to 11 hr is optimal (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004). However, as mentioned before, children's self-report did not give any hints toward signs of increased tiredness the next morning, nor did the

parental interviews indicate that the allocated 9 hr would be an unusually short bedtime for their children. Also, the children after sleep had generally faster reaction times, with this decrease similar to that observed across the wake interval, which likewise argues against possible unspecific influences of sleep inertia, as well as of lacking motor practice during sleep on motor system activation, that might have impaired SRTT performance. Finally, assuming that sleep-related effects on memory consolidation increase with increasing sleep duration, a slightly shorter-than-optimal sleep duration in the children would be expected to reduce rather than reverse the effect on implicit learning.

Presently, we cannot but speculate about the mechanisms underlying the sleep-dependent deterioration of implicit memories in children. There is considerable evidence that sleep during development, like in adulthood, supports brain plasticity, including synaptic processes presumed to underlie memory formation (e.g., Shaffery, Sinton, Bissette, Roffwarg, & Marks, 2002; Frank, Issa, & Stryker, 2001; Marks, Shaffery, Oksenberg, Speciale, & Roffwarg, 1995) Thus, the overnight deterioration in implicit memory cannot be taken to argue against a general facilitation of brain plasticity during sleep in children. Notably, our findings of impaired implicit memory performance agree with findings from a recent study in young zebra finches indicating reduced structure in an imitated song after overnight sleep (Deregnaucourt et al., 2005). The authors suggested that the postsleep deterioration of performance reflects a compromise between competing demands of plasticity and consolidation during skill learning. Specifically, they suggested that reprocessing of the recently acquired song representations during sleep in the absence of sensory feedback exerts a labilizing influence on the acquired song representations, which allows a more effective shaping of the behavior during subsequent training periods. Thereby, the less structured song in the morning provides the bird, with ongoing practice, repeated opportunities to explore its vocal abilities and optimize imitation. In this view, children with a pronounced deterioration in sleep-dependent memory consolidation are expected to develop the strongest implicit skill on the SRTT with repeated training over the long term.

Another explanation for the sleep-dependent deterioration of SRTT performance in children refers to developmental changes in the brain structures recruited for SRTT performance. Neuroimaging studies in adults have identified a network of brain regions activated during the implicit acquisition of sequential regularities that includes, among others, mainly fronto-striatal circuitry and the hippocampus (Schendan, Searl, Melrose, & Stern, 2003; Rose, Haider, Weiller, & Buchel, 2002). Comparing 7- to 11-year-old children and adults, Thomas et al. (2004) demonstrated that activity in the right caudate was significantly correlated with reaction time measures

of implicit learning on an SRTT in both age groups. However, the groups differed in the recruitment of hippocampal activity during learning. The adults showed relatively enhanced activity in the right hippocampus to structured (compared to random) sequence trials, suggesting that they relied to a significantly greater extent than the children on hippocampal function during SRTT learning. Importantly, the neuronal reactivation of newly acquired memory representations during sleep, which is assumed to underlie the memory function of sleep, has been found to grasp both the hippocampus and the striatum (Pennartz, Lee, Verheul, Lipa, Barnes, & McNaughton, 2004; Ribeiro & Nicolelis, 2004; Wilson & McNaughton, 1994). The reactivations, which take place mainly during SWS, can occur in these structures in close temporal association, suggesting a functional linkage (Pennartz et al., 2004). In fact, there is strong evidence, based mainly on spatial motor tasks in adult animals and humans, indicating that increased task familiarity in the course of training is associated with preferential striatal over hippocampal activation (Burgess, Maguire, & O'Keefe, 2002; Packard & Knowlton, 2002), and this process in adults is probably enhanced by sleep after training (Orban et al., 2006). Moreover, for different learning tasks, a competitive interference between striatal and hippocampal systems has been shown (Packard & Knowlton, 2002; Schroeder, Wingard, & Packard, 2002; Poldrack et al., 2001). In this framework, opposite effects of sleep on implicit learning in children and adults might reflect that sleep in children leads to a preferential strengthening of hippocampal aspects of the memory representation, whereas sleep in adults strengthens caudate involvement. This view would implicate that sleep-associated memory consolidation in the children pertained to a greater extent to explicit aspects of the task interfering with speed indicators of implicit learning (Born & Wagner, 2004; Poldrack et al., 2001; Jimenez, Mendez, & Cleeremans, 1996). Indeed, sleep-associated explicit memory formation interfering with measures of implicit learning, under certain conditions, can occur in adults as well (Fischer, Drosopoulos, Tsen, & Born, 2006; Wagner et al., 2004). In the latter study, subjects were unable to generate the sequence structure of an SRTT when explicitly asked immediately after training, but were able to do so when asked after a night of sleep after training. Notably, although sleep enhanced consolidation of explicit sequence knowledge in this study, it did not improve measures of implicit sequence learning, suggesting that competition between the memory systems continues during sleep-associated off-line processing. Unfortunately, in the present study, no such direct performance measures of explicit knowledge were obtained.

Eventually, our view, relating the sleep-dependent deterioration of implicit knowledge in children to the preferential formation of representations that are linked to hippocampus-dependent explicit features of the task,

receives further support from a number of studies indicating that these memories benefit particularly from SWS, whereas implicit memories show a greater benefit from REM sleep (Drosopoulos, Wagner, & Born, 2005; Gais & Born, 2004; Peigneux et al., 2004; Mednick, Nakayama, & Stickgold, 2003; Wagner, Hallschmid, Verleger, & Born, 2003; Plihal & Born, 1997). Compared with the adults, sleep in our children was hallmarked by a preponderance of SWS, whereas amounts of REM sleep were comparable in both groups, with this shift in sleep structure implicating that overall sleep favored the processing of hippocampus-dependent memories. Nevertheless, any interpretation of the unexpected decrease in memory consolidation of implicit knowledge in children presently remains tentative and in need of further experimental substantiation.

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