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The Effects of Sleep Restriction and Extension on School-Age Children: What a Difference an Hour Makes

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This study assessed the effects of modest sleep restriction and extension on children's neurobehavioral functioning (NBF). The sleep of 77 children (age: $M = 10.6$ years; $range = 9.1–12.2$ years) was monitored for 5 nights with activity monitors. These children (39 boys and 38 girls) were all attending regular 4th- and 6th-grade classes. Their NBF was assessed using computerized tests on the 2nd day of their normal sleep schedule. On the 3rd evening, the children were asked to extend or restrict their sleep by an hour on the following 3 nights. Their NBF was reassessed on the 6th day following the experimental sleep manipulation. Sleep restriction led to improved sleep quality and to reduced reported alertness. The sleep manipulation led to significant differential effects on NBF measures. These effects may have significant developmental and clinical implications.

The role of sleep in learning, memory, and other neurobehavioral functions has been extensively studied. It has been demonstrated that experimental manipulations of sleep can influence learning and memory function and that intensified learning and training can influence sleep or have correlates in brain functioning during sleep (Maquet, 2001; Pilcher & Huffcutt, 1996). However, limited experimental research has been focused on the role of sleep restriction and extension in child development.

In a recent study we identified a significant relationship between sleep fragmentation and neurobehavioral functioning (NBF) in school-age children (Sadeh, Gruber, & Raviv, 2002). We found that an increased number of night wakings and lower sleep efficiency were associated with compromised NBF. Sleep duration was not correlated with NBF in this correlative naturalistic study. The goal of the present study was to assess the effects of moderate experimental changes in sleep duration on NBF in school-age children.

Sleep and NBF in Children

Many studies have demonstrated that sleep problems and sleep fragmentation are associated with learning difficulties or with compromised NBF (Blunden, Lushington, & Kennedy, 2001; Gozal, 1998; Sadeh et al., 2002). However, the correlative nature of these studies precludes any causal interpretation.

Most naturalistic studies have failed to document relationships between sleep duration per se and school performance or NBF. In some studies, an inconsistent or a phase-shifted sleep schedule was correlated with poorer functioning (Bates, Viken, Alexander, Beyers, & Stockton, 2002; Epstein, Chillag, & Lavie, 1998; Meijer, Habekothe, & van den Wittenboer, 2000; Wolfson & Carskadon, 1998). The most direct information on the effects of sleep duration on NBF comes from studies that have used sleep deprivation or sleep restriction and extension paradigms.

The effects of sleep deprivation and sleep restriction on NBF have been studied extensively in adults (Bonnet, 1994; Pilcher & Huffcutt, 1996). The most profound effects of sleep deprivation have been documented in the area of cognitive or NBF (Bonnet, 1994; Peigneux, Laureys, Delbeuck, & Maquet, 2001; Pilcher & Huffcutt, 1996). Pilcher and Huffcutt (1996) performed a meta-analysis of 56 sleep-deprivation studies and concluded that sleep deprivation leads to a significant impairment to human performance. Recent studies have suggested that executive control, located in the prefrontal cortex, is the system that is most sensitive to sleep deprivation, sleep disorders, or reduced alertness (Dahl, 1996; Drummond & Brown, 2001; Horne, 1993; Jones & Harrison, 2001).

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Only a small number of sleep-deprivation studies have been performed with children, and their conclusions were not consistent (Carskadon, Harvey, & Dement, 1981a, 1981b; Fallone, Acebo, Arnedt, Seifer, & Carskadon, 2001; Randazzo, Muehlbach, Schweitzer, & Walsh, 1998). In studying the effects of full-night sleep deprivation (Carskadon et al., 1981b) and 4-hr sleep restriction (Carskadon et al., 1981a), Carskadon and colleagues reported compromised functioning only following the full-night deprivation, suggesting the sleep restriction may not lead to significant consequences. Recent research challenges these findings and suggests that sleep restriction does lead to detectable deficits in NBF and that tracking these consequences may depend on the level of complexity of NBF that is tested. For example, Randazzo et al. (1998) compared the performance of children following sleep restriction to 5 hr in bed with the performance of a control group with 11 hr in bed. Compared with the control group, performance after 5 hr in bed was poorer on measures of verbal creativity and on the Wisconsin Card Sorting Test. No differences were found on less complex memory tasks (Randazzo et al., 1998). In a similar study, Fallone et al. (2001) compared children and adolescents (8 to 15 years of age) following a night of optimized sleep (based on their normal sleep habits) with children following sleep restriction to 4 hr of sleep. Following sleep restriction, the children were more sleepy and inattentive. However, tests of response inhibition and sustained attention revealed no significant differences in performance. The results of these sleep-restriction studies suggest that the effects of modest sleep deprivation could be detected by exploring specific areas of NBF that are most sensitive to variations in sleep and alertness (i.e., complex tasks that require executive control).

From a slightly different angle, early school start time could also be considered as a sleep-restricted schedule (Carskadon, Wolfson, Acebo, Tzischinsky, & Seifer, 1998; Epstein et al., 1998). Using questionnaire-based methods, these studies indicated that early school start time is associated with shorter sleep, increased daytime sleepiness, poorer concentration, and attention problems (Epstein et al., 1998).

Sleep debt and the associated reduced alertness could result from an acute event of extreme sleep deprivation (e.g., a single sleepless night) or by gradual accumulated sleep loss (e.g., a few successive nights of modest or moderate sleep restriction). This topic of acute versus accumulated sleep loss relates to whether people can adjust to a gradual ''sleep diet'' and learn to compensate physiologically by improving sleep quality or to adapt to functioning with less sleep. Studies on cumulative sleep restriction have shown cumulative negative effects on NBF, daytime and nocturnal EEG, mood, and sense of well-being (Dinges et al., 1997; Drake et al., 2001). In an interesting study, Drake et al. (2001) compared rapid versus cumulative sleep loss of 8 hr and found more significant impairments on tests of alertness, memory, and performance following rapid sleep loss compared with the slow accumulation of a comparable amount of sleep loss. The authors concluded that some compensatory adaptive mechanisms are involved in cumulative sleep loss and thus mitigate its effects. This topic of the accumulative effects of modest sleep loss has never been studied in children. The purpose of our study was to examine the effects of 3 nights of modest (± 1 hr) sleep restriction or extension on children's NBF.

Goals of the Present Study

Our review of the literature detected only a small number of studies that have experimentally tested the effects of sleep restriction and extension in children. All these studies were conducted in the laboratory and were based on a single night of drastic curtailment of sleep.

The daily struggles between children and their parents usually occur at home and are often limited to modest changes in sleep. Persistent battles on topics such as ''just one more TV show'' raise the scientific question ''What difference does an hour make?'' The goal of the present study was to investigate the effects of 1 hr of sleep restriction or extension, maintained on 3 successive nights at home, on NBF in children. To increase sensitivity of the design, our protocol was based on repeated (baseline-manipulation) testing design.

We designed our research to test the following three hypotheses: (a) most children would be able to restrict or extend their sleep on demand in their natural home environment, (b) sleep restriction would lead to improved sleep quality compared with sleep extension, and (c) sleep restriction would lead to an increase in reported fatigue and to compromised NBF compared with sleep extension.

Method

Participants

Seventy-seven children, 39 boys and 38 girls, participated in the study. These children participated in an earlier study (Sadeh et al., 2002) and they all agreed to participate in this second study when approached 2 years later (100% consent from available children and their parents). The study was approved and supported by the Israel Ministry of Education. Participating children and their parents signed informed consent forms.

The children were recruited from regular classes in two distinct age groups: fourth grade ($N = 42$, M age = 9.80 years, $SD = .64$) and sixth grade ($N = 35$; age: $M = 11.58$ years, $SD = .50$). Two classes for each grade level were included in this sample. An early attempt to include second-grade students indicated that younger children and their parents found it more difficult to comply with the sleep restriction and extension requirements of the study; therefore, second-grade students were not included.

Most of the children were living with both parents (90.9%), and slightly less than half (42.1%) were first born. Parents' ages ranged from 32 to 55 (age of fathers: $M = 43.57$ years, $SD = 4.53$; age of mothers: $M = 40.43$ years; $SD = 4.28$). Number of children in the family ranged from one to seven ($M = 2.96$, $SD = 1.03$). Most fathers (97.2%) and about half of the mothers (50.7%) held a full-time job.

Exclusion criteria included the following: (a) acute or chronic physical illness, (b) use of medication, or (c) reported developmental or psychiatric disorder.

Procedure

Each child completed the study according to a 6-day protocol, which overlapped with the Israeli 6-day school week (Sunday to Friday). On Day 1, each child received a package that included the actigraph and daily reports that were used to assess sleep and related parameters over the 6-day period. During Days 1 and 2, the child was instructed to sleep as he or she regularly sleeps. In the morning of Day 1 or 2 (between 8:00 a.m. and 10:00 a.m.) the child's baseline NBF was tested using the Neuropsychological Evaluation System (NES; Arcia, Ornstein, & Otto, 1991; Sadeh et al., 2002).

In the afternoon of Day 3, the children and their parents received a phone call indicating to them how to modify the child's sleep schedule for the following 3 days. According to a random assignment, 40 children were asked to go to sleep 1 hr earlier and 37 were asked to go to sleep 1 hr later than their regular bedtime (see Figure 1 for examples of responsive and nonresponsive children). Previous research showed that the morning rise time is robust (around 7:00 a.m.) during school days (Sadeh, Raviv, & Gruber, 2000). On the morning of Day 6, after 3 consecutive nights of required alteration of sleep schedule, the children were retested with the NES at the same time they had been tested in the morning of their first test administration (between 8:00 a.m. and 10:00 a.m.). This schedule was stricly adhered to in order to control for time-of-day effects on NBF (Sadeh et al., 2002). The study was performed during the school year between November and May.

Measures

The main instruments used in this study for assessing sleep and NBF have been used and validated in developmental research (Sadeh et al., 2002; Sadeh et al., 2000).

Actigraphy. Activity monitoring and daily sleep logs were used to assess sleep–wake patterns. The actigraph is a wristwatch-like device that uses a piezo-electric beam to detect movement. The detected movements are translated into digital counts accumulated across predesigned epoch intervals (e.g., 1 min) and stored in the internal memory. The actigraph can collect data continuously over an extended period (1 week or longer). Data are downloaded to the computer using special interface unit.

Actigraphy has been established as a reliable and valid method for the naturalistic study of sleep in infants, children, and adults (Sadeh & Acebo, 2002; Sadeh, Hauri, Kripke, & Lavie, 1995). Recent studies have also demonstrated good reliability of these actigraphic measures (Acebo et al., 1999; Sadeh et al., 2002; Sadeh et al., 2000).

The children were asked to attach the miniature actigraph (a wristwatch-like device, Mini Motionlogger, Ambulatory Monitoring Inc.) to their nondominant wrist in the evening when preparing for sleep and to remove it in the morning (see Figure 1). Sleep assessment was performed for 5 continuous nights during school days. The actigraphs collected data in 1-min epochs and in amplifier setting 18, which is the standard mode for sleep–wake scoring. Actigraphic files were analyzed with the Actigraphic Scoring Analysis program (ASA) for an IBM-compatible PC that provides validated sleep–wake measures (Sadeh, Sharkey, & Carskadon, 1994).

Actigraphic sleep measures included: (a) sleep onset time, (b) morning rise time, (c) sleep period—total time from sleep onset time to morning awakening time, (d) true sleep time—sleep time excluding all periods of wakefulness, (e) sleep percent—percentage of true sleep time (Measure 4) from total sleep period (Measure 3), (f) number of

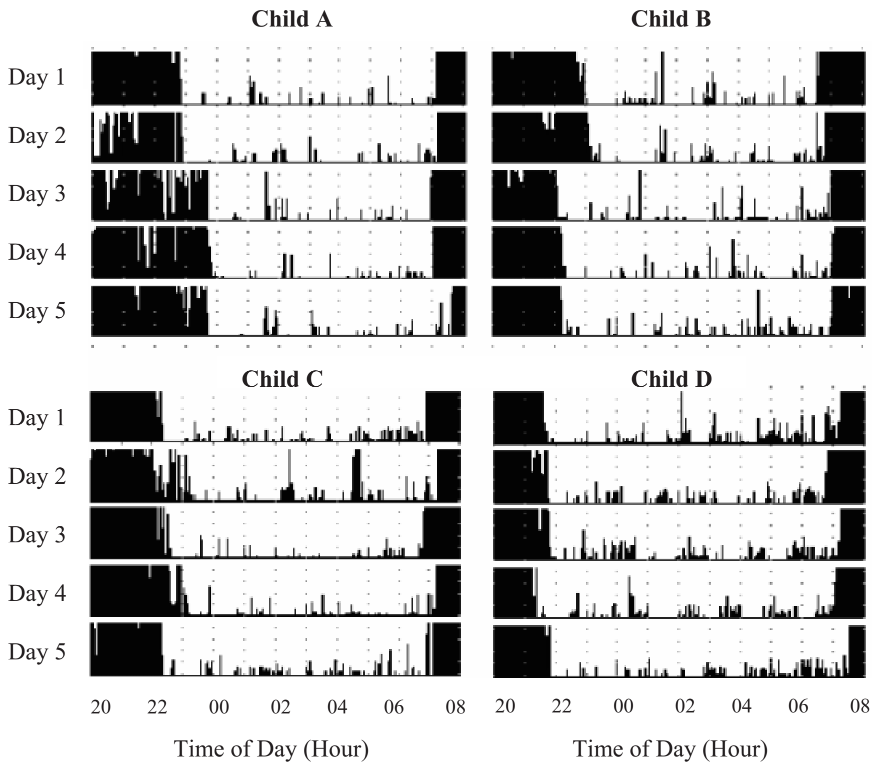

Figure 1. Examples of children's responses to the sleep restriction and extension protocol: Raw nocturnal activity data of 4 children (A, B, C, and D). Each panel represents the raw activity data of 1 child for 5 consecutive nights. Dark areas represent increased activity level associated with wakefulness (before sleep onset, after morning awakening time, and during night wakings). Child A responded to the sleep restriction protocol and fell asleep significantly later on the 3 manipulation nights (starting on the third night). Child B responded to the sleep extension protocol and fell asleep significantly earlier on the 3 manipulation nights. Children C and D did not respond to the experimental manipulation.

night wakings, and (g) quiet sleep—percentage of motionless sleep.

Daily sleep–wake diaries. The subjective daily information reported by the children included the following measures: (a) lights-off time, (b) morning rise time, (c) number of night wakings, (d) sleep quality—a 4-point scale ranging from 0 (*very good*) to 3 (*bad*), (e) duration to fall asleep—a 4-point scale ranging from 0 (*less than 5 min*) to 3 (*more than 30 min*), (f) evening fatigue—a 3-point scale ranging from 0 (*very alert*) to 2 (*very sleepy*), and (g) morning fatigue—a 3-point scale ranging from 0 (*very alert*) to 2 (*very sleepy*). These measures have been used and validated in previous research (Sadeh et al., 2000).

NES. The NES was originally developed for adults but it has been successfully used with school-age children (Arcia et al., 1991; Sadeh et al., 2002). In a recent study, the NES measures demonstrated good test–retest reliability and were sensitive to sleep and time-of-day variations (Sadeh et al., 2002).

The tests were presented to the children by a research assistant who also monitored their performance on the practice trials and provided further guidance when needed. Once the practice trials were completed on each test, the children continued to the test trials.

The children were tested twice (baseline and postintervention) with the NES installed on a Compaq notebook computer (Contura model). Six age-appropriate tests were administered:

1. Finger tapping test. Task: to tap as fast as possible with one finger on a single button. Tested domain: motor speed. Variable: maximum number of taps.
2. Simple reaction-time test. Task: to press a button as quickly as possible when a large square appears on the screen. Tested domains: vigilance and motor reaction. Variable: average reaction time.
3. Continuous performance test (CPT). Task: to respond as fast as possible to a specific animal presented and to avoid responding to any other animal. Tested domains: sustained visual attention, response inhibition, and motor

speed. Variables: average reaction time, omission errors (not responding to target stimulus), and commission errors (responding to nontarget stimulus).

4. Symbol–digit substitution (SDS). Task: Nine symbols and nine digits are paired at the top of the screen and the child is requested to press the digits on the keyboard corresponding to a test set of the nine symbols presented in a mixed order. Six sets of nine symbol–digit pairs were presented in succession. Tested domains: visual memory, visual scanning, visual-motor speed. Variable: average response latency for completing each set.
5. Visual digit span test. Task: to recall presented sequences of digits and to repeat the sequence on the computer keyboard (forward) or to repeat the digits in reversed order (backward). Longer spans are increasingly presented until the child makes two errors in a span length. Tested domains: working memory, attention. Variables: lengths of the longest span answered correctly forward and backward.
6. Serial digit learning test. Task: to 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 eight trials is reached. Tested domain: working memory, learning strategies. Variable: an error score that is the sum of the errors over all trials attempted.

Results

The Effects of the Experimental Manipulation on Sleep

To assess the effects of the experimental manipulation on the actigraphic sleep measures and the subjective reports, we used ANOVAs with gender, age (fourth and sixth grades), and group (sleep-restriction or sleep-extension group) as the between-subject variables, and period (baseline vs. intervention) as the within-subject independent variable. Actigraphic and subjective sleep measures were used as the dependent variables (see Table 1).

Significant Group × Period interaction effects were found for the following actigraphic sleep measures (see Figure 2): sleep onset time, sleep period, sleep percent, true sleep time, quiet sleep, and

Table 1
The Effects of Sleep Manipulation on Sleep Measures: Means (± SDs) and F Values

	Group		
Sleep measure	Sleep restricted	Sleep extended	F(1, 69) Time*Group
Sleep onset time (hr)			139.17***
Baseline	22.23 ± .52	22.20 ± .73	
Intervention	23.01 ± .68	21.56 ± .59	
Morning rise time (hr)			2.47
Baseline	6.96 ± .36	6.81 ± .30	
Intervention	7.04 ± .43	6.74 ± .29	
Sleep period (min)			88.66***
Baseline	523.7 ± 29.7	516.3 ± 43.5	
Intervention	482.1 ± 36.2	551.0 ± 34.7	
True sleep time (min)			69.44***
Baseline	488.6 ± 29.3	487.7 ± 43.0	
Intervention	457.1 ± 38.3	516.9 ± 40.2	
Sleep percent (%)			8.50**
Baseline	93.33 ± 3.54	94.50 ± 3.74	
Intervention	94.78 ± 3.02	93.77 ± 3.48	
Night wakings (N)			10.46**
Baseline	1.64 ± 1.18	1.34 ± 1.22	
Intervention	1.20 ± 0.89	1.81 ± 1.25	
Quiet sleep (%)			6.03*
Baseline	70.00 ± 9.08	71.70 ± 9.97	
Intervention	71.55 ± 9.68	70.00 ± 8.68	

*$p < .05$.
**$p < .005$.
***$p < .001$.

number of night wakings. These interactions reflected the fact that sleep was significantly extended from baseline to intervention period in the sleep-extension group (by an average of 35 min) and that sleep was significantly shortened in the sleep-restriction group (41 min). These effects resulted from the significant changes in sleep onset, whereas morning rise time was not affected. In addition, the results reflect changes in sleep quality in response to the manipulation. Sleep quality was significantly improved in the sleep-restriction group as manifested in increased sleep percent and quiet sleep and reduced number of night wakings following intervention, whereas the opposite changes occurred in the sleep-extension group.

Significant Group × Period interactions were also found on the following subjective measures (see Figure 2): reported evening fatigue, $F(4, 61) = 8.61$, $p < .001$; predicted sleep latency, $F(4, 61) = 2.80$, $p < .05$; and reported sleep latency, $F(4, 61) = 3.40$, $p < .01$. No significant interactions were found for reported sleep quality and reported morning alertness. The significant interactions (see Figure 2) indicated that compared with advancing sleep onset, delaying sleep onset resulted in increased evening fatigue and predicted and reported shorter sleep latency.

The analyses revealed significant age differences. Compared with the younger age group (fourth grade), older children (sixth grade) had delayed sleep onset time, $F(1, 69) = 41.25$, $p < .001$; shorter sleep period, $F(1, 69) = 35.65$, $p < .001$; shorter true sleep time, $F(1, 69) = 23.03$, $p < .001$; and increased percent of quiet sleep, $F(1, 69) = 6.7$, $p < .05$. Significant gender differences were also found. Compared with boys, girls had higher sleep percent, $F(1, 69) = 7.42$, $p < .01$, and higher quiet sleep percent, $F(1, 69) = 14.83$, $p < .001$.

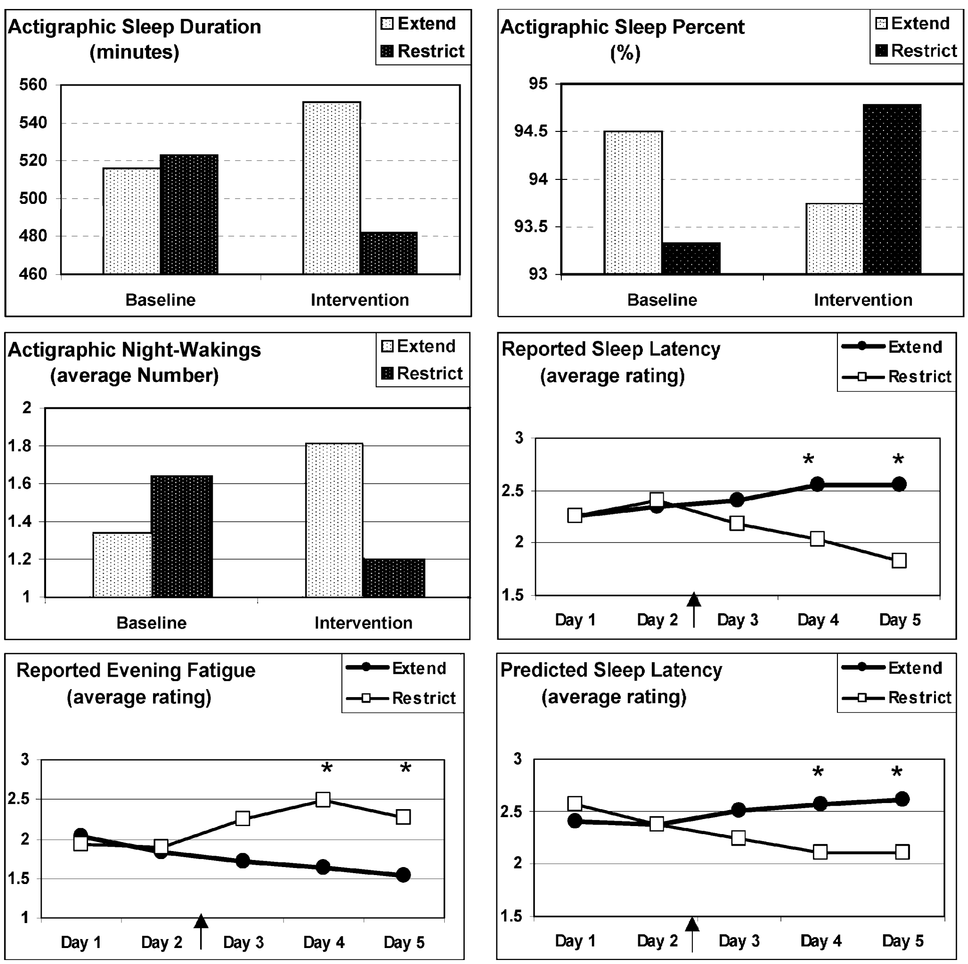

Figure 2. Effects of the experimental manipulation on actigraphic and reported sleep measures. *$p < .05$ in post hoc comparisons (extension vs. restriction). Arrows indicate point of experimental intervention.

To examine individual compliance with our experimental manipulation of sleep, we set a criterion that compliance would be defined as restriction or extension (according to the assignment) of sleep period by an average of at least 30 min. Sixty-five percent of the children in the sleep-restriction group and 62% of the children in the sleep-extension group met the compliance criteria. Thirty-six percent of the children failed to extend or restrict their sleep by an average of 30 min or longer (14 children from each manipulation group, similarly distributed in the two age groups). No other behavioral or background variables distinguished between the compliant and noncompliant participants.

The Effects of the Experimental Manipulation on NBF

To analyze the effects of the experimental manipulation on NBF, we divided the participants into three groups according to the participants' success in meeting the demands of the sleep manipulation. Children who extended their sleep by an average of 30 min or more during the intervention days were defined as the sleep-extension group (SEG). Children who shortened their sleep by an average of 30 min or more were defined as the sleep-restriction group (SRG). Children who failed to extend or shorten their sleep by at least 30 min were defined as the no-change group (NCG). Because of technical failures in one of the two administrations of the NES in 5 children, only 72 children were included in the final analyses (SEG: $N = 21$; SRG: $N = 28$; NCG: $N = 23$).

The analyses were based on ANOVAs with gender, age (fourth and sixth grades), and Group (SRG, SEG, and NCG) as the between-subject independent variables, and period (baseline vs. intervention) as the within-subject repeated independent variable. The NES measures were used as the dependent variables (see Table 2).

Significant Group $\times$ Period interactions were found on three NES measures (see Figure 3): simple reaction time, digit forward, and the reaction time on the CPT. These interactions and the post hoc tests indicated that children who extended their sleep significantly improved their performance (from baseline to postintervention period) on the digit forward memory test, whereas the performance of the other groups did not change. On the CPT, children in the SEG significantly improved their reaction time, whereas the performance of children in the other groups (SRG and NCG) did not change significantly. On the simple reaction time test, performance of the children from the SRG and the NCG significantly deteriorated whereas performance of the children from the SEG remained stable.

Additional Findings

The NES measures were found to be sensitive to age differences. Compared with the younger children, older children had higher numbers of finger tappings, $F(1, 60) = 8.22$, $p < .01$; shorter simple reaction times, $F(1, 60) = 6.82$, $p < .05$; shorter reaction time on symbol–digit test, $F(1, 60) = 25.21$, $p < .001$; higher scores on digit forward test, $F(1, 60) = 16.90$, $p < .001$; higher scores on digit backward test, $F(1, 60) = 16.86$, $p < .001$; shorter reaction times on the CPT, $F(1, 60) = 12.79$, $p < .001$; and better scores on the digit learning test, $F(1, 60) = 14.84$, $p < .001$. Gender differences were found on one NES measure. Compared with girls, boys had higher numbers of finger tappings, $F(1, 60) = 8.04$, $p < .01$.

Significant main period (practice) effects were also found, reflecting the repeated testing effects. Compared with the first administration, performance on the second administration was characterized by longer reaction times on the simple reaction time test, $F(1, 60) = 16.18$, $p < .001$; shorter latencies on the symbol–digit substitution test, $F(1, 60) = 18.67$, $p < .001$; higher scores on the digit backward memory test, $F(1, 60) = 4.83$, $p < .05$; and better performance on the digit learning test, $F(1, 60) = 10.01$, $p < .005$.

Discussion

Our study was aimed at exploring the effects of manipulating sleep time on NBF of normal children. Whereas most of the existing literature is based on drastic experimental manipulation of sleep, we tested the effects of a modest manipulation that we consider more similar to everyday life experiences of children and their parents. The use of actigraphy enabled this intervention study in the natural environment of the children. However, it should be noted that actigraphic sleep assessment is based on activity measurement and some errors are likely to occur compared with polysomnographic sleep measures. Our results show that most children were motivated enough and were able to comply and extend or restrict their sleep according to their random assignment.

The manipulation of sleep time resulted in an average reduction of 41 min from the sleep period in the SRG on 3 consecutive nights. Children in the SEG

Table 2
The Effects of Sleep Manipulation (Group) on Neurobehavioral Functioning: Means (± SDs) and F Values

	Group				
NES measure	Sleep restricted	No change	Sleep extended	*F*(1, 61) Time	*F*(2, 61) Time*Group
Tapping				0.00	0.28
Baseline	149.8 ± 15.0	152.8 ± 20.4	151.2 ± 17.8		
Intervention	149.7 ± 14.9	152.2 ± 19.3	151.5 ± 18.6		
Simple RT				16.2**	3.94*
Baseline	431.4 ± 82.5	412.2 ± 73.1	414.2 ± 50.2		
Intervention	458.2 ± 77.1	461.7 ± 74.6	418.7 ± 58.4		
Symbol–Digit RL				18.7***	1.06
Baseline	2429 ± 399	2530 ± 504	2405 ± 411		
Intervention	2337 ± 415	2335 ± 421	2275 ± 390		
CPT–RT				0.98	6.74**
Baseline	641.0 ± 55.7	633.3 ± 45.4	615.8 ± 73.5		
Intervention	639.9 ± 61.1	650.1 ± 60.9	587.8 ± 67.8		
CPT–Om Err				0.02	0.28
Baseline	1.57 ± 1.17	1.43 ± 1.56	1.00 ± 0.63		
Intervention	1.32 ± 1.09	1.48 ± 0.90	1.00 ± 1.04		
CPT–Com Err				0.18	0.75
Baseline	0.89 ± 1.42	0.57 ± 1.04	0.48 ± 1.33		
Intervention	1.03 ± 1.29	0.83 ± 1.03	0.29 ± 0.46		
Digit span FW				0.05	3.25*
Baseline	5.61 ± 0.69	5.17 ± 0.83	5.43 ± 0.98		
Intervention	5.25 ± 0.89	5.22 ± 1.09	5.71 ± 0.90		
Digit span BW				4.83*	0.71
Baseline	4.14 ± 0.89	4.35 ± 1.07	4.43 ± 1.29		
Intervention	4.36 ± 1.16	4.52 ± 1.04	5.05 ± 1.32		
Digit learning ES				10.00**	0.23
Baseline	2.79 ± 2.69	3.43 ± 3.64	2.67 ± 2.13		
Intervention	2.04 ± 1.57	2.30 ± 2.30	1.71 ± 2.45		

Note. Intervention groups: neurobehavioral (NES) measures: tapping = number of finger tappings, RL = response latency, Om Err = omissions errors, Com Err = commissions errors, FW = forward, BW = backward, ES = error score.
*$p < .05$.
**$p < .005$.
***$p < .001$.

extended their sleep period by an average of 35 min. These results indicate that most children can extend or restrict their sleep period on demand with a small incentive. Furthermore, most of the children who went to sleep earlier managed to fall asleep earlier than their regular bedtime. These findings are consistent with earlier reports, based on laboratory studies, that children and adults can extend their sleep given the opportunity of extended bedtime period (Carskadon, Keenan, & Dement, 1987; Webb, 1986).

The manipulation of sleep time resulted in significant changes in sleep quality measures. Sleep extension led to a significant increase in the number of night wakings and to a reduction of sleep percent. The opposite was true for sleep restriction. These effects are in accord with earlier findings of increased slow-wave sleep and sleep efficiency on subsequent nights following experimental sleep restriction (Devoto, Lucidi, Violani, & Bertini, 1999; Webb & Agnew, 1975). These results have been attributed to the work of physiological compensatory mechanisms that regulate sleep physiology in response to variations in sleep duration.

The operation of these compensatory mechanisms that lead to improvement of sleep quality in response to sleep restriction strengthens the question of whether these small variations in sleep duration could lead to any detectable effects on alertness and NBF. Our results suggest that in spite of the operation of these compensatory mechanisms, the subjective reports and the NBF of the children echoed the changes in sleep duration.

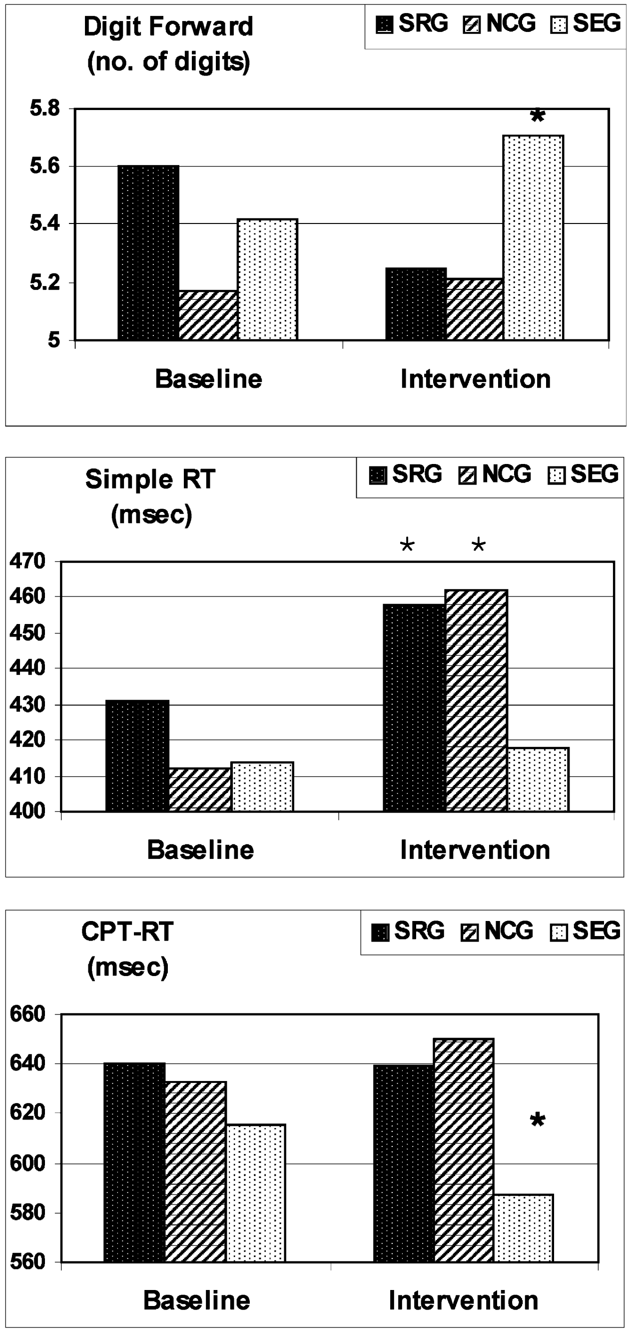

Figure 3. Effects of the experimental manipulation on neurobehavioral functioning. SRG = sleep-restricted group; SEG = sleep-extended group; NCG = no-change group. *$p < .05$ in post hoc comparisons (intervention vs. baseline).

The subjective daily reports reflected significant effects of the experimental manipulation on the children's perceived fatigue and sleepiness. These changes included significantly higher ratings of fatigue in the evening, and reported predicted and estimated shorter sleep latency following sleep restriction compared with sleep extension. These results are consistent with earlier findings, based on the Multiple Sleep Latency Test, showing reduced sleep latencies in children following sleep restriction (Carskadon et al., 1981b).

Before addressing the effects of the experimental manipulation on NBF we should note that significant repeated measurement effects were found from baseline to intervention assessment on some of the NBF measures. For instance, on the simple reaction time, overall the children's performance on the second administration was worse (slower reaction time) than on the first administration. This could be attributed to the children's loss of interest because of the repetitive and ''boring'' nature of the task. However, because there is no reason to assume distinct practice effects (other then those attributed to the manipulation itself), the interaction between the manipulation group and administration (baseline vs. intervention) could be attributed only to the effect of the manipulation.

In addition, the experimental manipulation of sleep duration led to distinct effects on performance patterns on a number of neurobehavioral tests. The significant Group $\times$ Period interaction on the digit forward memory test indicated that extension of sleep lead to improved memory function as compared with sleep restriction or no change in sleep duration. Furthermore, sleep extension led to improved performance on the CPT. Sleep extension maintained performance on a simple reaction time test, whereas performance was significantly when sleep was restricted or when there was no change in sleep duration. These findings suggest that moderate changes in sleep duration have detectable significant effects on children's neuropsychological functioning.

The effects on NBF on the CPT, reaction time, and memory tests have significant implications for learning and school performance. These measures have been found to be significantly correlated with classroom behaviors and achievement tests (Arcia et al., 1991). For instance, digit span scores were highly correlated with reading ($r = .56$) and mathematics ($r = .58$) scores on the California Achievement Test. For better appreciation of the size of the manipulation effects, it should be noted that the size of the differential effect of the extension–restriction manipulation on the NES measures was larger than or similar to the highly significant age differences between the fourth- and sixth-grade students on these measures. It could be interpreted that the manipulation effects on these neurobehavioral functions are similar to those gained by 2 years of development.

It is also important to emphasize that the CPT, which was found to be sensitive to sleep extension and restriction in this study, was also found to be sensitive to sleep fragmentation in our earlier study (Sadeh et al., 2002). The CPT is a task that has been associated with sustained attention and behavioral inhibition (Corkum & Siegel, 1993). Behavioral inhibition has become a key construct in understanding developmental psychopathology (Barkley, 1997; Gray, 1990; Nigg, 2000). Therefore, our findings suggest that the consequences of variations in sleep duration could be widespread, with developmental and clinical implications.

Our findings that modest modifications of sleep time have significant effects on NBF may appear in conflict with our earlier findings that under normal sleep conditions, sleep time was not correlated with NBF (Sadeh et al., 2002). However, the absence of significant correlations does not imply that the children in our naturalistic study were getting sufficient sleep or that the two phenomena are not related. Theoretically, similar results could have been obtained if the children were all sleep deprived or were getting excessive sleep. Earlier research has demonstrated that alertness and NBF could be compromised by either fragmented sleep (Jones & Harrison, 2001; Wesensten, Balkin, & Belenky, 1999) or by insufficient sleep (Drummond & Brown, 2001; Pilcher & Huffcutt, 1996). Our studies suggest that these effects are highly relevant during childhood and that children are sensitive to modest alteration of their natural sleep duration.

Our results have significant clinical and educational implications. They highlight the need for parents and professionals to be aware of the consequences of insufficient sleep in children and the potential benefits of sleep extension. The results suggest that most children can extend their sleep and gain demonstrable benefits from even modest sleep extension. From a clinical perspective, it has been suggested that the consequences of insufficient sleep could also affect behavioral regulation and lead to or exacerbate developmental psychopathology (Dahl, 1996). Professionals should consider whether children who present with clinical problems associated with insufficient sleep could benefit from better management of their sleep schedule.

We regret that the results of our study, as well as many other studies in the field, do not provide a clear answer to the question of how much sleep is needed for children at different ages. Our results emphasize, however, that for the individual child, variations in sleep duration could have a clear impact on his or her NBF. Parents and child care professionals can explore the appropriate sleep needs of a specific child by experimenting with extending or restricting sleep, tracking the changes in the child's behavior and well-being, and finding the child's optimal sleep needs. We believe that this is done intuitively, if not systematically, by many parents.

References

Acebo, C., Sadeh, A., Seifer, R., Tzischinsky, O., Wolfson, A. R., Hafer, A., et al. (1999). Estimating sleep patterns with activity monitoring in children and adolescents: How many nights are necessary for reliable measures? *Sleep*, *22*, 95–103.

Arcia, E., Ornstein, P. A., & Otto, D. A. (1991). Neurobehavioral Evaluation System (NES) and school performance. *Journal of School Psychology*, *29*, 337–352.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65–94.

Bates, J. E., Viken, R. J., Alexander, D. B., Beyers, J., & Stockton, L. (2002). Sleep and adjustment in preschool children: Sleep diary reports by mothers relate to behavior reports by teachers. *Child Development*, *73*, 62–75.

Blunden, S., Lushington, K., & Kennedy, D. (2001). Cognitive and behavioural performance in children with sleep-related obstructive breathing disorders. *Sleep Medicine Reviews*, *5*, 447–461.

Bonnet, M. H. (1994). Sleep deprivation. In W. C. Dement (Ed.), *Principles and practice of sleep medicine* (2nd ed., pp. 50–67). Philadelphia: Saunders.

Carskadon, M. A., Harvey, K., & Dement, W. C. (1981a). Acute restriction of nocturnal sleep in children. *Perceptual and Motor Skills*, *53*, 103–112.

Carskadon, M. A., Harvey, K., & Dement, W. C. (1981b). Sleep loss in young adolescents. *Sleep*, *4*, 299–312.

Carskadon, M. A., Keenan, S., & Dement, W. C. (1987). Nighttime sleep and daytime sleep tendency in preadolescents. In C. Guilleminault (Ed.), *Sleep and its disorders in children* (pp. 43–52). New-York: Raven Press.

Carskadon, M. A., Wolfson, A. R., Acebo, C., Tzischinsky, O., & Seifer, R. (1998). Adolescent sleep patterns, circadian timing, and sleepiness at a transition to early school days. *Sleep*, *21*, 871–881.

Corkum, P. V., & Siegel, L. S. (1993). Is the continuous performance task a valuable research tool for use with children with attention-deficit-hyperactivity disorder? *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *34*, 1217–1239.

Dahl, R. E. (1996). The regulation of sleep and arousal: Development and psychopathology. *Development and Psychopathology*, *8*, 3–27.

Devoto, A., Lucidi, F., Violani, C., & Bertini, M. (1999). Effects of different sleep reductions on daytime sleepiness. *Sleep*, *22*, 336–343.

Dinges, D. F., Pack, F., Williams, K., Gillen, K. A., Powell, J. W., Ott, G. E., et al. (1997). Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. *Sleep*, *20*, 267–267.

Drake, C. L., Roehrs, T. A., Burduvali, E., Bonahoom, A., Rosekind, M., & Roth, T. (2001). Effects of rapid versus slow accumulation of eight hours of sleep loss. *Psychophysiology*, *38*, 979–987.

Drummond, S. P. A., & Brown, G. G. (2001). The effects of total sleep deprivation on cerebral responses to cognitive performance. *Neuropsychopharmacology*, *25*, S68–S73.

Epstein, R., Chillag, N., & Lavie, P. (1998). Starting times of school: Effects on daytime functioning of fifth-grade children in Israel. *Sleep*, *21*, 250–256.

Fallone, G., Acebo, C., Arnedt, J. T., Seifer, R., & Carskadon, M. A. (2001). Effects of acute sleep restriction on behavior, sustained attention, and response inhibition in children. *Perceptual and Motor Skills*, *93*, 213–229.

Gozal, D. (1998). Sleep-disordered breathing and school performance in children. *Pediatrics*, *102*, 616–620.

Gray, J. A. (1990). Brain systems that mediate both emotion and cognition. *Cognition and Emotion*, *4*, 269–288.

Horne, J. A. (1993). Human sleep, sleep loss and behaviour. Implications for the prefrontal cortex and psychiatric disorder. *British Journal of Psychiatry*, *162*, 413–419.

Jones, K., & Harrison, Y. (2001). Frontal lobe function, sleep loss and fragmented sleep. *Sleep Medicine Reviews*, *5*, 463–475.

Maquet, P. (2001). The role of sleep in learning and memory. *Science*, *294*(5544), 1048–1052.

Meijer, A. M., Habekothe, H. T., & van den Wittenboer, G. L. H. (2000). Time in bed, quality of sleep and school functioning of children. *Journal of Sleep Research*, *9*, 145–153.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*, 220–246.

Peigneux, P., Laureys, S., Delbeuck, X., & Maquet, P. (2001). Sleeping brain, learning brain. The role of sleep for memory systems. *Neuroreport*, *12*(18), A111–A124.

Pilcher, J. J., & Huffcutt, A. I. (1996). Effects of sleep deprivation on performance: A meta-analysis. *Sleep*, *19*, 318–326.

Randazzo, A. C., Muehlbach, M. J., Schweitzer, P. K., & Walsh, J. K. (1998). Cognitive function following acute sleep restriction in children ages 10–14. *Sleep*, *21*, 861–868.

Sadeh, A., & Acebo, C. (2002). The role of actigraphy in sleep medicine. *Sleep Medicine Reviews*, *6*, 113–124.

Sadeh, A., Gruber, R., & Raviv, A. (2002). Sleep, neurobehavioral functioning and behavior problems in school-age children. *Child Development*, *73*, 405–417.

Sadeh, A., Hauri, P. J., Kripke, D. F., & Lavie, P. (1995). The role of actigraphy in the evaluation of sleep disorders. *Sleep*, *18*, 288–302.

Sadeh, A., Raviv, A., & Gruber, R. (2000). Sleep patterns and sleep disruptions in school-age children. *Developmental Psychology*, *36*, 291–301.

Sadeh, A., Sharkey, K. M., & Carskadon, M. A. (1994). Activity-based sleep–wake identification: An empirical test of methodological issues. *Sleep*, *17*, 201–207.

Webb, W. B. (1986). Enhanced slow sleep in extended sleep. *Electroencephalography and Clinical Neurophysiology, 64*, 27–30.

Webb, W. B., & Agnew, H. W. (1975). The effects on subsequent sleep of an acute restriction of sleep length. *Psychophysiology, 12*, 367–370.

Wesensten, N. J., Balkin, T. J., & Belenky, G. (1999). Does sleep fragmentation impact recuperation? A review and reanalysis. *Journal of Sleep Research*, *8*, 237–245.

Wolfson, A. R., & Carskadon, M. A. (1998). Sleep schedules and daytime functioning in adolescents. *Child Development*, *69*, 875–887.