Journal of Experimental Child Psychology 144 (2016) 184–198

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Temperament moderates the association between sleep duration and cognitive performance in children

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A R T I C L E   I N F O

Article history:
Received 18 May 2015
Revised 25 November 2015
Available online 4 January 2016

Keywords:
Preadolescents
Sleep duration
Temperament
Attention
Inhibition
Working memory

A B S T R A C T

The importance of sufficient sleep for cognitive performance has been increasingly recognized. Individual differences in susceptibility to effects of sleep restriction have hardly been investigated in children. We investigated whether individual differences in temperament moderate the association of sleep duration with sustained attention, inhibition, and working memory in 123 children (42% boys) aged 9 to 11 years. Sleep duration was assessed using parental diaries, and temperament traits of extraversion and negative affectivity were assessed by child self-report (Early Adolescent Temperament Questionnaire–Revised). Computerized assessment of sustained attention (short-form Psychomotor Vigilance Task, PVT), inhibition (PVT Go/No-Go adaptation), and working memory (visual Digit Span) were performed at school. Our findings

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http://dx.doi.org/10.1016/j.jecp.2015.11.014

demonstrate that long-sleeping introverted and negatively affective children show *worse* sustained attention and working memory than short-sleeping children with these temperaments.

Introduction

An adequate amount of sleep is important for children's development. Habitual sleep duration has shown to be highly variable among children (Jenni & Carskadon, 2012; Jenni, Molinari, Caflisch, & Largo, 2007) and is dependent on multiple factors such as age, sleep problems, and temperament (El-Sheikh & Buckhalt, 2005; Gau, 2000; Moore, Slane, Mindell, Burt, & Klump, 2011). Total sleep duration (hours per night) declines with age; for children aged 9 to 11 years, habitual sleep duration is on average approximately 10 h (Iglowstein, Jenni, Molinari, & Largo, 2003; Laberge et al., 2001; Szymczak, Jasinska, Pawlak, & Zwierzykowska, 1993). Studies showed that inadequate sleep in school-age children has a negative impact on multiple domains, including more internalizing and externalizing behavioral problems (Astill, Van der Heijden, Van IJzendoorn, & Van Someren, 2012; Sadeh, Gruber, & Raviv, 2002), an increased risk of obesity (Cappuccio et al., 2008), and poorer cognitive and academic performance (Astill et al., 2012; Buckhalt, El-Sheikh, Keller, & Kelly, 2009; Dewald, Meijer, Oort, Kerkhof, & Bogels, 2010). Studying the association between sleep duration and cognitive performance is highly relevant given that (a) approximately one out of three children suffers from sleep problems (Fricke-Oerkermann et al., 2007; Mindell & Meltzer, 2008), (b) a considerable decline in children's sleep duration has been found over the last decennia (Matricciani, Olds, & Petkov, 2012), and (c) there is an increase in the use of electronic devices (e.g., computers, mobile phones) that compromise sleep when used in the evening (Cain & Gradisar, 2010).

Studies employing experimental curtailment of sleep in children aged 9 to 14 years (Carskadon, Harvey, & Dement, 1981; Sadeh, Gruber, & Raviv, 2003) indicate that task performance is affected by sleep deprivation as well as by multiple nights of sleep restriction. Even a single night of restricted sleep to 5 h resulted in performance decrements in verbal creativity and cognitive flexibility in children aged 10 to 14 years (Randazzo, Muehlbach, Schweitzer, & Walsh, 1998) but did not impair performance of response inhibition and sustained attention tasks in children aged 8 to 15 years (Fallone, Acebo, Arnedt, Seifer, & Carskadon, 2001). Furthermore, children aged 10 to 12 years who started school earlier than usual, and consequently slept 24 min less than their counterparts with regular school start times, complained significantly more of daytime fatigue, sleepiness, and concentration difficulties (Epstein, Chillag, & Lavie, 1998). Detrimental effects are not only found in studies on short-term sleep restriction. A longitudinal study showed that a period of relatively short sleep (<10 h) during early childhood related to worse performance on tasks several years later in development, even when sleep had normalized during the last years before cognitive assessment (Touchette et al., 2007).

Although the association between sleep and cognitive performance was frequently studied during the past decades, more research is needed to describe factors that can moderate this association. Individual differences in the sensitivity to sleep restriction on cognitive performance have been demonstrated in adults (Van Dongen, Baynard, Maislin, & Dinges, 2004) but have remained elusive in children. It is important to identify children who are sensitive to sleep restriction because the extensive and long-term consequences might be preventable with appropriate sleep interventions. Previous research in adults (Killgore, Richards, Killgore, Kamimori, & Balkin, 2007; Rupp, Killgore, & Balkin, 2010; Taylor & McFatter, 2003) suggests that temperament could moderate the effect of sleep restriction on cognitive performance. Temperament is the innate inclination to behave in particular ways such as extraversion (i.e., the ease of a child to approach novel stimuli or situations) and negative affectivity/neuroticism (i.e., the proneness to experience feelings of fear, anger, and sadness). Temperament has shown to be relatively stable across various kinds of situations and over the course of time (Zentner & Bates, 2008).

The link between extraversion and sensitivity to sleep restriction concerns temperament-related individual differences in the general level of physiological arousal. Sleep restriction lowers the daytime physiological arousal level (Cote, Milner, Osip, Baker, & Cuthbert, 2008). Arousal levels that are too low (or too high) are disadvantageous for information processing (Aston-Jones & Cohen, 2005; Yerkes & Dodson, 1908). Sleep restriction, therefore, may affect individuals with a low intrinsic arousal level more than individuals with a high baseline arousal level. Extraverted people have a relatively low baseline arousal level indicated by strong alpha activity in the resting state electroencephalogram (EEG) (Hagemann et al., 2009). Studies in adults (Killgore et al., 2007; Rupp et al., 2010; Taylor & McFatter, 2003) showed that extraverts have marked performance decrements after sleep restriction, whereas this is less pronounced in introverts. As explained by Killgore and colleagues (2007), the more highly aroused reticulo–thalamic–cortical activation system of introverts provided protection against the decreased arousal and associated attentional declines produced by sleep restriction. Whether this also applies to children is still unknown.

No previous studies addressed the role of the temperament trait negative affectivity in the association between sleep and cognitive performance in children, although indirect evidence revealed that children with a lower vagal tone, a physiological marker for high negative affectivity, are more sensitive to negative effects of sleep reduction (El-Sheikh, Erath, & Keller, 2007). Studies in adults, however, found no association between neuroticism and performance decrements after sleep deprivation (Killgore et al., 2007; Taylor & McFatter, 2003).

The current study is the first to investigate whether extraversion and negative affectivity/neuroticism moderate the association between sleep duration and cognitive performance in children. We hypothesized that shorter sleep duration is associated with poor cognitive performance in children with high extraversion or negative affectivity, whereas the association is weaker/absent for children who score low on extraversion or negative affectivity.

Method

Participants

Participants were 123 children (42% boys, 97% Dutch nationality), aged 9 to 11 years ($M = 10.5$ years, $SD = 0.8$), recruited from primary schools across The Netherlands from January to June 2012. Of 50 contacted schools, 12 gave consent for participation. Parents received information, and 130 parents and children (80% of those who gave informed consent) filled out the questionnaires. Parents' educational level was relatively high, with 91% of the respondents and 89% of their partners having completed secondary (vocational) education, higher professional education, or university. Children with a psychiatric diagnosis and/or using psychotropic medication as reported by parents, were excluded (attention deficit/hyperactivity disorder with medication [$n = 5$] and anxiety disorder [$n = 2$]).

Procedure

The study was approved by the local university ethics committee. All parents gave written informed consent. A research week was planned during which the parent and child filled out questionnaires and sleep diaries on the Netherlands Sleep Registry (NSR) internet platform (http://www.sleepregistry.nl). Questionnaires concerned demographic data, sleep characteristics, and temperament. On the last day of the research week (Tuesdays to Fridays), cognitive tasks were administered in fixed order between 10:00 and 17:00 at school using the NSR platform.

Instruments

Sleep duration

An online 7-day sleep diary was kept by parents for 1 week. It contained questions about time lights went off, minutes the child needed to fall asleep (sleep onset latency [SOL]), and time of final awakening. On average, parents completed 6.85 days (SD = 1.96), and 83% of the parents filled out the daily sleep diary on the respective day or within 2 days after that. Parental sleep diaries have shown satisfactory agreement with objective actigraphy data in school-age children (Werner, Molinari, Guyer, & Jenni, 2008). Sleep duration was calculated as the time interval from sleep onset (lights out + SOL) until final awakening for each night and averaged over all available days. A missing value was recorded if only 3 days or less were available.

Temperament

The Early Adolescent Temperament Questionnaire–Revised (EATQ-R) is a self-report questionnaire, with 65 Likert-type scale items, used to measure reactive and regulative temperament traits in children aged 9 to 15 years (Ellis & Rothbart, 2001). It consists of four main temperament factors: extraversion/surgency (comprising high-intensity pleasure, low levels of shyness, and low levels of fear), negative affectivity (fear and frustration), effortful control, and affiliativeness (Hartman, 2000). We included only extraversion and negative affectivity (13 items each) in our analyses because these are common temperament traits that were associated with sleep-related changes in arousal. The EATQ-R has adequate psychometric properties in community samples, Cronbach's alphas between .61 and .74, and moderate to good test–retest stability. Its validity is supported by associations with several other self-report measures of personality, including strong positive correlations between EATQ-R temperament factors (extraversion and negative affectivity) and Eysenck's personality factors (extraversion and neuroticism) (Ellis & Rothbart, 2001; Muris & Meesters, 2009; Muris, Meesters, & Blijlevens, 2007). In our sample, the internal consistency of the two temperament factors used was acceptable (extraversion: Cronbach's $\alpha = .78$; negative affectivity: $\alpha = .75$).

Tasks

Psychomotor Vigilance Task

An optimized 3-min version of the Psychomotor Vigilance Task (PVT) (Basner, Mollicone, & Dinges, 2011) was used to assess sustained attention. This brief version of the PVT has been validated in conditions of total and partial sleep deprivation and approximates sensitivity for fatigue-related changes in alertness of the standard 10-min PVT (Basner et al., 2011). Participants monitored a square on the computer screen and pressed a button as quickly as possible each time a counter appeared within the square. After pressing, the counter stopped and displayed the reaction time (RT) in milliseconds for 1 s. The feedback aims at motivating participants to respond as quickly as possible. In case of no response, the counter stopped after 10 s and a new stimulus was presented. In 3 min, a maximum of 48 trials were displayed, and the interstimulus intervals varied randomly between 2 and 5 s. Outcome variables were mean RT (responses were regarded valid if RT $\geqslant$ 100 ms), number of lapses (RT $\geqslant$ 500 ms) (Basner et al., 2011; Peters et al., 2009), and time on task slowing of responsiveness (respective changes in mean RT from the first to last 1-min tertile). Justification of the lapse threshold and time on task effect can be found in Part A of the online Supplementary material.

PVT Go/No-Go

Inhibitory capacity was tested using a Go/No-Go adaptation of the 3-min PVT described above. The Go/No-Go paradigm is widely used and has adequate psychometric properties with moderate to high test–retest stability and adequate discriminant validity in children (Kindlon, Mezzacappa, & Earls, 1995) and good test–retest reliability and internal consistency in adults (Wöstmann et al., 2013). Children monitored a gray square on the screen and pressed a button if a counter appeared within the square (Go trials). However, when a red square appeared simultaneously with the counter, children needed to suppress their inclination to respond and wait for the next stimulus (No-Go trials). Equal to the PVT, a maximum of 48 trials with interstimulus intervals of 2 to 5 s were displayed in 3 min. Go trials versus No-Go trials were randomly chosen with equal probability. In case of no response, a new stimulus was presented after 10 s for Go trials and after 2 s for No-Go trials. As the outcome measure, we used the percentage correct rejections, that is, the absence of a response within a period of 2 s after onset of No-Go trials (higher scores indicate better inhibitory capacities). Because speed may be traded for accuracy, depending on response strategy, we also calculated the "inhibition cost" ($\text{Inhibition}_{\Delta RT}$), that is, the increase in RT on Go trials of the Go/No-Go version relative to RT on the normal PVT (see Part B of online Supplementary material).

Digit Span

Working memory capacity was assessed using the visual Digit Span task, which is an adaptation of the auditory Digit Span task (Wechsler, 2005). The visual Digit Span task has been successfully used in several studies (Sadeh et al., 2002; Sadeh et al., 2003; Stiles, McGregor, & Bentler, 2012). Sequences of digits were displayed on the screen for 2 s. After a sequence disappeared, children needed to reproduce the sequence in the same order (forward condition) or in reversed order (backward condition) by typing the numbers on the keyboard. Each condition started with two numbers; the digit sequence was presented twice with different numbers and then increased in length by one digit. The procedure stopped after two consecutive errors at the same sequence length. The outcome measure is the number of digits in the longest correctly repeated sequence (both forward and backward).

Statistical analyses

Descriptive statistics and histograms were used to verify normality of the variables concerning sleep duration, temperament traits, and cognition. Boxplots and scatterplots were used to detect univariate and bivariate outliers, respectively. Extreme univariate outliers (>±3 *SD*) were identified and excluded: PVT mean RT ($n = 1$), PVT lapses ($n = 3$), PVT time on task ($n = 3$), PVT Go/No-Go ($n = 6$), and $\text{Inhibition}_{\Delta RT}$ ($n = 2$). No bivariate outliers were detected. Normality (standardized skewness and kurtosis between −3 and 3) did not apply to PVT mean RT, number of lapses, time on task, PVT Go/No-Go percentage correct rejections, and $\text{Inhibition}_{\Delta RT}$ (Table 1). Blom transformations were successful in normalizing those variables.

Mixed effect regression analyses were performed to examine moderation effects of temperament on the association between sleep duration and cognitive variables. Sleep duration and temperament variables were centered at their mean to prevent multicollinearity between predictors and the interaction term (Aiken & West, 1991). Separate regression analyses were performed for each temperament factor (extraversion and negative affectivity). In each analysis, sex, age, and parents' educational level (as indicator for socioeconomic status [SES]) were entered first to control for possible gender, age, and SES effects on cognitive functioning. Second, sleep duration and temperament (main effects) were included in the model. The interaction term was entered in the third step. We reported and interpreted the main effects of sleep duration and temperament from the full interaction model. To interpret and visualize significant interaction effects, simple regression analyses (controlled for sex, age, and SES) were performed and scatterplots were made in which the association of sleep duration with the cognitive outcome measure was examined at three different temperament levels (tertile rating): low (−1 *SD*), average, and high (+1 *SD*). Standardized regression coefficients (β) indicate effect sizes, which can be considered as small ($.10 \leqslant \beta < .30$), moderate ($.30 \leqslant \beta < .50$), or large ($\beta \geqslant .50$) (Cohen, 1988). All statistical assumptions regarding mixed effect regression analyses (i.e., independent errors, linearity, and homoscedasticity) were met. The analyses were conducted with SPSS (Statistical Package for Social Sciences) Version 21.0. An alpha level of .05 (two-sided) was used to indicate statistical significance.

Table 1
Descriptive statistics of the study variables.

	N	*M*	*SD*	Min	Max	Standardized skewness	Standardized kurtosis
Sleep duration							
Average sleep duration whole week (h:min)	110	9:54	0:33	8:21	11:14	−0.45	−0.18
Temperament[a]							
Extraversion	115	36.29	9.15	14.00	55.00	−0.42	−1.21
Negative affectivity	115	36.13	8.41	13.00	53.00	−0.72	−0.15
Sustained attention							
PVT mean RT (ms)	117	359.81	66.27	229.33	568.81	5.69	3.39
PVT number of lapses (⩾500 ms)	115	3.23	3.82	0	18	9.70	10.83
PVT time on task[b] (ms)	115	15.26	39.81	−114.97	164.78	−0.76	5.10
Inhibition							
PVT Go/No-Go (% correct rejections)	113	81.11	18.79	15.38	100.00	−7.59	6.76
$\text{Inhibition}_{\Delta RT}$[c] (ms)	115	219.59	111.35	−29.25	725.09	7.34	10.20
Working memory							
Digit Span forward	120	5.40[d]	0.99	3	8	0.56	0.73
Digit Span backward	120	4.47[d]	1.15	1	7	−1.15	0.50

Note. PVT, Psychomotor Vigilance Task.
[a] Higher score (range = 13–65) indicates more of the trait.
[b] Time on task = PVT mean RT tertile 3 – PVT mean RT tertile 1.
[c] $\text{Inhibition}_{\Delta RT}$ = mean RT Go trials – mean RT PVT.
[d] Average recalled sequence length on Digit Span backward was significantly lower, $t(119) = 8.28$, $p < .001$, than on Digit Span forward.

Results

Table 1 provides an overview of the descriptive statistics of all variables. Sleep data were missing in 13 children, and the EATQ-R was incomplete for 8 children. On the cognitive tasks, some data were missing (PVT [$n = 5$], PVT Go/No-Go [$n = 4$], and Digit Span [$n = 3$]) due to illness of the children on the day of assessment or due to technical problems. Sleep duration (h:min) during weekdays (M = 9:56, SD = 0:33) and weekends (M = 9:55, SD = 0:49) was not different, $t(92) = 0.24$, $p = .809$. Therefore, we used average sleep duration for the whole week in the analyses. Sleep duration declined with age ($r = -.25$, $p = .009$); the average sleep durations (with standard deviations in parentheses) for children aged 9 years ($n = 28$), 10 years ($n = 50$), and 11 years ($n = 32$) were 10:07 (0.28), 9:54 (0.32), and 9:44 (0.35), respectively.

No gender differences were found on sleep duration, temperament, sustained attention, or inhibition. Girls performed significantly better than boys on Digit Span forward, $t(118) = -2.04$, $p = .044$, $d = 0.38$, and Digit Span backward, $t(118) = -2.15$, $p = .033$, $d = 0.40$. Significant associations were found between age and some cognitive outcome measures: PVT mean RT ($r = -.35$, $p < .001$), PVT number of lapses ($r = -.31$, $p = .001$), PVT Go/No-Go percentage correct rejections ($r = .27$, $p = .003$), and Digit Span forward ($r = .22$, $p = .014$). Performance on these tasks improved as age increased. SES was significantly associated with sleep duration ($r = -.21$, $p = .025$) but not with cognitive functioning except for Digit Span forward ($r = .20$, $p = .025$).

Main effect of sleep duration

Sustained attention. Regression analyses revealed no significant main effect of sleep duration on sustained attention (i.e., PVT mean RT, PVT number of lapses, and PVT time on task) (Table 2).
Inhibition. Sleep duration was not significantly associated with the percentage correct rejections on the PVT Go/No-Go or with response slowing ($\text{Inhibition}_{\Delta RT}$) (Table 3).
Working memory. For Digit Span forward, regression analyses showed no significant main effect of sleep duration (Table 4). For Digit Span backward, a significant negative main effect of sleep duration was found, indicating that longer average sleep duration was related to worse performance on the Digit Span backward task.

Main effect of temperament

Sustained attention. Higher levels of extraversion were associated with faster responses and a decreased number of lapses. Low negative affectivity was related to faster responses. None of the temperament traits was associated with PVT time on task (Table 2).

Inhibition. Extraversion and negative affectivity were not associated with percentage correct rejections on the PVT Go/No-Go. Only extraversion was significantly related to $\text{Inhibition}_{\Delta RT}$. Response slowing was larger for more introverted children (Table 3).

Working memory. None of the temperament traits was a significant predictor for Digit Span forward or Digit Span backward (Table 4).

Table 2
Results of regression analyses with sleep duration, temperament, and Sleep Duration × Temperament interaction on sustained attention controlled for sex, age, and SES.

	Sustained attention								
	PVT mean RT (n = 101)			PVT number of lapses (n = 100)			PVT time on task[a] (n = 98)		
	β	t	p	β	t	p	β	t	p
Extraversion									
Sex	.04	0.43	.669	−.09	−0.93	.356	−.17	−1.51	.134
Age	−.34	−3.76	<.001	−.29	−3.01	.003	.01	0.11	.914
SES	−.05	−0.51	.610	<−.01	<−.01	.997	−.10	−0.91	.367
Sleep duration	.06	0.60	.550	.05	0.47	.641	−.01	−0.11	.911
Temperament	−.37	−4.07	<.001	−.23	−2.32	.022	−.07	−0.65	.518
Sleep Duration × Temperament	−.21	−2.35	.021	−.20	−2.07	.041	−.06	−0.54	.589
Negative affectivity									
Sex	.13	1.37	.173	−.02	−0.24	.812	−.14	−1.34	.185
Age	−.32	−3.40	.001	−.28	−2.83	.006	.01	0.07	.943
SES	−.09	−0.89	.373	−.05	−0.46	.645	−.12	−1.07	.290
Sleep duration	.01	0.10	.918	<−.01	−0.02	.988	−.03	−0.27	.791
Temperament	.25	2.58	.011	.07	0.69	.493	.01	0.12	.902
Sleep Duration × Temperament	.19	2.03	.046	.24	2.39	.019	.06	0.56	.579

Note. PVT, Psychomotor Vigilance Task; SES, socioeconomic status (indicated by parents' educational level).
[a] Time on task = PVT mean RT tertile 3 – PVT mean RT tertile 1.

Table 3
Results of regression analyses with sleep duration, temperament, and Sleep Duration × Temperament interaction on inhibition controlled for sex, age, and SES.

	Inhibition					
	PVT Go/No-Go (% correct rejections) (n = 97)			$\text{Inhibition}_{\Delta RT}$[a] ($n$ = 99)		
	β	t	p	β	t	p
Extraversion						
Sex	.13	1.27	.206	−.12	−1.20	.235
Age	.32	3.20	.002	−.05	−0.47	.639
SES	−.05	−.48	.632	−.13	−1.23	.224
Sleep duration	.19	1.75	.083	.04	0.33	.742
Temperament	−.17	−1.68	.097	−.24	−2.40	.018
Sleep Duration × Temperament	−.01	−0.12	.902	−.15	−1.55	.124
Negative affectivity						
Sex	.15	1.48	.141	−.07	−0.63	.531
Age	.33	3.21	.002	−.03	−0.31	.755
SES	−.07	−0.67	.503	−.15	−1.43	.155
Sleep duration	.21	1.95	.054	.01	0.06	.956
Temperament	.04	0.37	.712	.16	1.52	.132
Sleep Duration × Temperament	−.09	−0.85	.397	.12	1.16	.248

Note. PVT, Psychomotor Vigilance Task; SES, socioeconomic status (indicated by parents' educational level).
[a] $\text{Inhibition}_{\Delta RT}$ = mean RT Go trials – mean RT PVT.

Table 4
Results of regression analyses with sleep duration, temperament, and Sleep Duration × Temperament interaction on working memory controlled for sex, age, and SES.

	Working memory					
	Digit Span forward (n = 102)			Digit Span backward (n = 102)		
	β	t	p	β	t	p
Extraversion						
Sex	.20	1.99	.050	.18	1.87	.064
Age	.20	2.05	.044	.05	0.53	.595
SES	.09	0.90	.368	−.06	−0.64	.523
Sleep duration	−.12	−1.19	.236	−.32	−3.18	.002
Temperament	.18	1.81	.074	.11	1.16	.248
Sleep Duration × Temperament	.05	0.56	.580	.24	2.49	.015
Negative affectivity						
Sex	.16	1.65	.103	.13	1.44	.154
Age	.19	1.94	.055	.04	0.49	.624
SES	.10	1.01	.316	−.05	−0.50	.617
Sleep duration	−.11	−1.13	.263	−.23	−2.46	.016
Temperament	−.13	−1.32	.190	−.18	−1.95	.055
Sleep Duration × Temperament	−.02	−0.18	.857	−.34	−3.72	<.001

Note. SES, socioeconomic status (indicated by parents' educational level).

Moderation by temperament: Extraversion

Sustained attention. The effect of sleep duration on PVT mean RT was significantly moderated by extraversion ($\beta = -.21$, $t = -2.35$, $p = .021$). A similar effect was found for number of lapses ($\beta = -.20$, $t = -2.07$, $p = .041$). Figs. 1A and 1B show that for children who score low (−1 *SD*) on extraversion (introverts), longer sleep duration was associated with slower responses ($\beta = .59$, $t = 3.41$, $p = .002$) and more lapses ($\beta = .44$, $t = 2.33$, $p = .027$). The association between sleep duration and PVT performance was not significant for children with high (+1 *SD*) extraversion levels (RT: $\beta = -.28$, $t = -1.61$, $p = .117$; lapses: $\beta = -.34$, $t = -1.92$, $p = .065$) or for those with an average level of extraversion (RT: $\beta = -.08$, $t = -0.51$, $p = .617$; lapses: $\beta = .11$, $t = 0.61$, $p = .546$). As shown in Figs. S1A and S1B of the online Supplementary material, plotting sex, age, and SES corrected residuals of sleep duration against the residuals of PVT performance showed similar patterns as for the uncorrected figures. There was no significant interaction effect for PVT time on task (Table 2).
Inhibition. Extraversion did not significantly moderate the association between sleep duration and inhibition.
Working memory. No significant interaction effect was found for sleep duration and extraversion on Digit Span forward. The effect of sleep duration on Digit Span backward was significantly moderated by extraversion ($\beta = .24$, $t = 2.49$, $p = .015$). For children with low levels (−1 *SD*) of extraversion, longer sleep duration results in poorer working memory performance ($\beta = -.66$, $t = -4.11$, $p < .001$), whereas results for children with high levels (+1 *SD*) of extraversion ($\beta = .09$, $t = 0.54$, $p = .596$) and average levels of extraversion ($\beta = -.29$, $t = -1.55$, $p = .133$) were not significant (Fig. 2A; see also Fig. S2A in online Supplementary material).

Moderation by temperament: Negative affectivity

Sustained attention. Negative affectivity significantly moderated the effect of sleep duration on PVT mean RT ($\beta = .19$, $t = 2.03$, $p = .046$) and PVT number of lapses ($\beta = .24$, $t = 2.39$, $p = .019$). The results depicted in Figs. 1C and 1D (see also Figs. S1C and S1D in online Supplementary material) show that longer sleep duration is associated with worse sustained attention (PVT RT: $\beta = .57$, $t = 2.97$, $p = .007$; PVT lapses: $\beta = .44$, $t = 2.10$, $p = .047$) for children with high levels (+1 *SD*) of negative affectivity. Sleep duration and PVT performance were not significantly related for children with average levels of

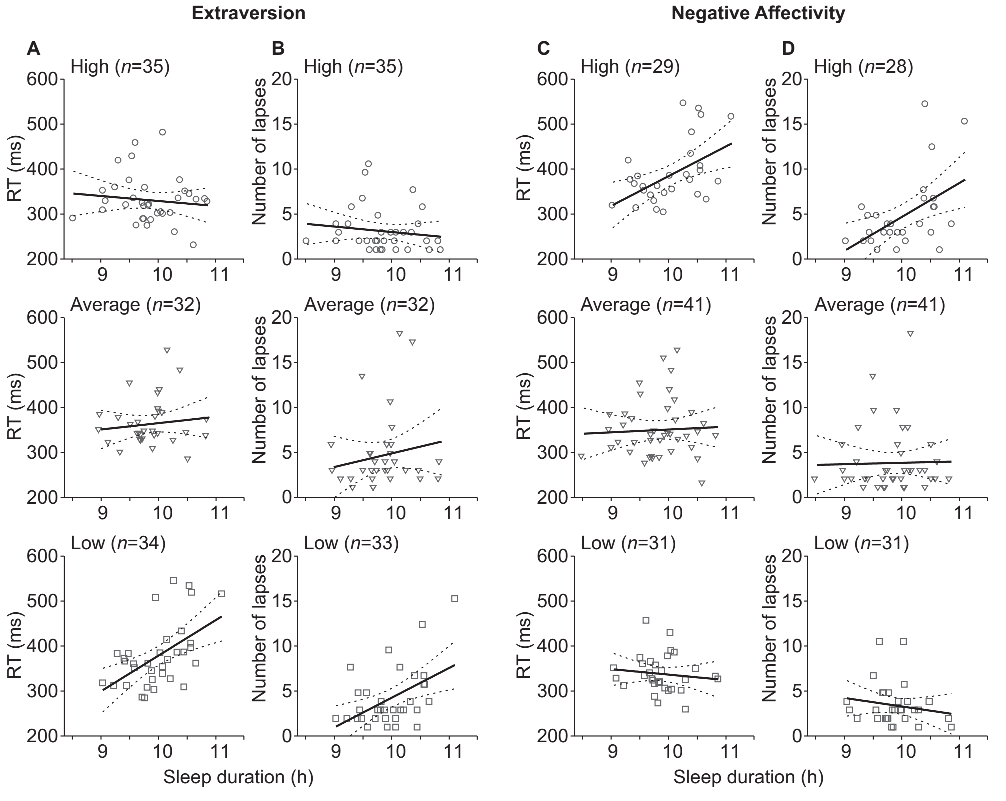

Fig. 1. (A,B) The association (with 95% confidence bounds) of Psychomotor Vigilance Task performance (A: mean reaction time [RT]; B: number of lapses in 3 min) with sleep duration differs depending on whether children score high (above group mean +1 *SD*) (upper panels), average (middle panels), or low (below group mean −1 *SD*) (lower panels) on extraversion. (C,D) Likewise, the association of Psychomotor Vigilance Task performance (C: mean reaction time [RT]; D: number of lapses) with sleep duration differs depending on whether children score high (above group mean +1 *SD*) (upper panels), average (middle panels), or low (below group mean −1 *SD*) (lower panels) on negative affectivity. Introverted children and children with high negative affectivity perform worse if they have a longer sleep duration.

negative affectivity (RT: $\beta = -.15$, $t = -0.96$, $p = .343$; lapses: $\beta = -.04$, $t = -0.25$, $p = .801$). For children with low (−1 *SD*) negative affectivity levels, longer sleep duration was associated with fewer PVT lapses ($\beta = -.39$, $t = -2.14$, $p = .042$) but not with faster RT ($\beta = -.29$, $t = -1.53$, $p = .137$). No significant effects were found for PVT time on task (Table 2).

Inhibition. No significant Sleep Duration × Temperament interaction was found on the PVT Go/No-Go outcome variables.

Working memory. For Digit Span forward, no significant interaction effect was found (Table 4). The association between sleep duration and Digit Span backward was moderated by negative affectivity ($\beta = -.34$, $t = -3.72$, $p < .001$). The association between sleep duration and Digit Span backward was negative and significant for children with high levels (+1 *SD*) of negative affectivity ($\beta = -.66$, $t = -3.67$, $p = .001$), indicating that longer sleep results in poorer working memory performance, whereas results for children with low (−1 *SD*) negative affectivity ($\beta = .13$, $t = 0.66$, $p = .516$) and average levels of negative affectivity ($\beta = -.31$, $t = -1.82$, $p = .076$) were not significant (Fig. 2B; see also Fig. S2B in online Supplementary material).

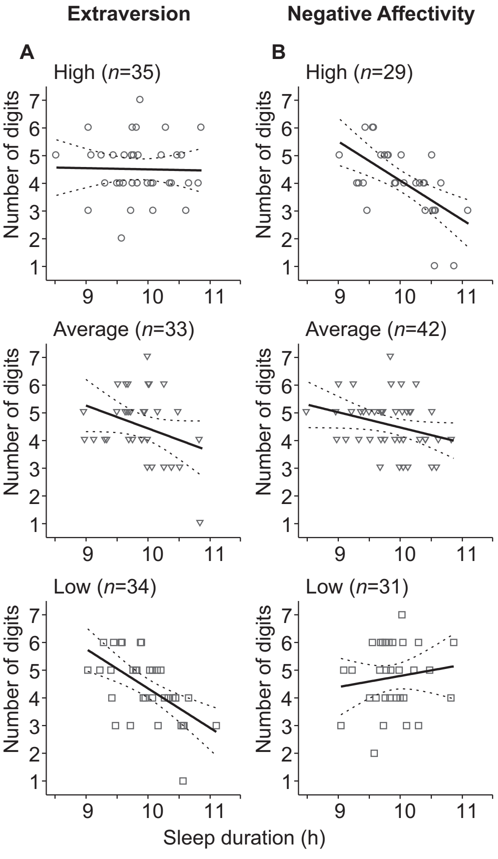

Fig. 2. The association (with 95% confidence bounds) of Digit Span backward performance (number of digits in the longest correctly repeated sequence) with sleep duration differs depending on whether children score high (above group mean +1 *SD*) (upper panels), average (middle panels), or low (below group mean −1 *SD*) (lower panels) on extraversion (A) and negative affectivity (B). Introverted children and children with high negative affectivity perform worse if they have a longer sleep duration.

Combining both temperament factors

Higher levels of negative affectivity were associated with low scores on extraversion ($r = .63$, $p < .001$). Therefore, we analyzed whether the Sleep Duration × Temperament interactions found on sustained attention and working memory showed shared variance or whether there was a unique contribution of both temperament factors. We included both temperament variables and interaction terms (i.e., Sleep Duration × Extraversion and Sleep Duration × Negative Affectivity) in one regression model. In case of sustained attention, both interaction terms Sleep Duration × Extraversion (PVT mean RT: $\beta = -.14$, $t = -1.24$, $p = .219$; PVT lapses: $\beta = -.10$, $t = -0.87$, $p = .389$) and Sleep Duration × Negative Affectivity (PVT mean RT: $\beta = .11$, $t = 0.93$, $p = .357$; PVT lapses: $\beta = .18$, $t = 1.42$, $p = .158$) lost significance in the presence of each other. For working memory, the interaction term Sleep Duration × Extraversion ($\beta < .01$, $t = 0.04$, $p = .965$) lost significance in the presence of the Sleep Duration × Negative Affectivity interaction ($\beta = -.34$, $t = -2.95$, $p = .004$).

Discussion

Our study is the first to investigate whether temperament traits moderate the association between sleep duration and cognitive functioning (sustained attention, inhibition, and working memory) in children aged 9 to 11 years.

Sleep duration and cognitive functions

Confirming a recent meta-analysis (Astill et al., 2012), no significant associations between sleep duration and sustained attention were found. Whereas this cognitive domain is sensitive to sleep restriction in adults, a lack of sensitivity has repeatedly been reported in children. This may represent a floor effect; the performance of well-rested children equals that of sleep-deprived adults, possibly due to not yet fully developed neural systems associated with sustained attention (Astill et al., 2012; Fair et al., 2007; Uddin, Supekar, & Menon, 2010).

In contrast to earlier findings (Gradisar, Terrill, Johnston, & Douglas, 2008; Steenari et al., 2003), we found that children who slept longer performed worse on the Digit Span backward task. This surprising result may be explained by the neural efficiency hypothesis, which argues that poor performing individuals have less efficient neural circuits (Haier et al., 1988). Consistently, Rypma, Berger, and D'Esposito (2002) found that low-performing persons showed less neural efficiency (i.e., overall more brain activation but less specific prefrontal cortex activation) during a working memory task than high-performing persons. The original neural efficiency hypothesis was extended by Geiger, Achermann, and Jenni (2010), who argued that children who sleep relatively longer show less efficient information processing (i.e., neuronal recovery) at night and, therefore, need more sleep. An alternative hypothesis for our contradicting results that longer sleep was related to worse performance is that children who spent more time in bed also had more nighttime awakenings or disrupted or fragmented sleep and, as has been shown in previous studies, poor sleep quality is associated with worse cognitive performance (Astill et al., 2012; Dewald et al., 2010; Sadeh et al., 2002).

The "neural efficiency" explanation implies a negative association between sleep duration and inhibition as well, whereas we found no association for PVT Go/No-Go accuracy and PVT Go/No-Go speed. Although this lack of effect of sleep duration on inhibition in children was also found by Fallone and colleagues (2001), it is in contrast to the general consensus that restricted sleep impairs inhibitory capacities (Astill et al., 2012; Drummond, Paulus, & Tapert, 2006; Lim & Dinges, 2010). It is suggested that the level of complexity of the cognitive skills tested may play a role in detecting associations with sleep, where tasks requiring high cognitive load are more sensitive (Bernier, Beauchamp, Bouvette-Turcot, Carlson, & Carrier, 2013; Sadeh et al., 2003). The tasks we used to measure sustained attention and inhibition are low in complexity. This possibly decreased the chance to detect significant effects.

Moderation by temperament

The temperament traits extraversion and negative affectivity moderated the association between sleep duration and the cognitive domains of sustained attention and working memory but not inhibition. In contrast to the findings in adults (Killgore et al., 2007; Rupp et al., 2010; Taylor & McFatter, 2003), we found that among the most introverted children and children with high levels of negative affectivity, worse performance related to longer, rather than shorter, sleep duration. Only in those children were longer sleepers less able to sustain attention, and they performed worse on working memory. Subsequent analyses suggest a common underlying mechanism for both extraversion and negative affectivity because of their shared variance. This mechanism might be related to baseline cortical arousal levels of introverted and highly negative affective children (Beauducel, Brocke, & Leue, 2006; Eysenck, 1967; Hagemann et al., 2009) that are higher than optimal for maximal performance according to the Yerkes–Dodson inverted U relation between performance and arousal (Yerkes & Dodson, 1908). Because sleep restriction lowers arousal (Cote et al., 2008; Sanders, 1983), a (limited) reduction in sleep duration may bring the arousal levels of introverts and children with high levels of negative affectivity closer to the optimum. Longer sleep duration might further enhance their arousal further away from the level that is optimal for performance. It should be noted, however, that the Yerkes–Dodson inverted U relation provides only a partial explanation. It would also predict a positive association between sleep duration and performance for the extraverted and least negative affective children because an increase in arousal level as a consequence of longer sleep would bring them closer to the level that is optimal for performance. Such an association was not present in our data except for one: For children with low levels of negative affectivity, sleep duration was negatively related to the number of lapses on the PVT. This is in line with a study of Mastin, Peszka, Poling, Phillips, and Duke

(2005) showing that extraverted and low neurotic adults were in fact the most resilient in performance (lapses of attention) following sleep deprivation. In conclusion, the Yerkes–Dodson inverted U relation holds only for the negative association of sleep duration with performance in the most "hyperaroused" children but is not in line with the lack of association in the most "underaroused" children. An alternative interpretation for the association between longer sleep duration and poor cognitive performance in introverted children and children with high levels of negative affectivity could be that common underlying factors are involved that simultaneously promote long sleep and poor cognitive performance in children with high introversion or negative affectivity.

Study evaluation and implications

This study has several limitations. First, we used parental sleep diaries with data on time lights out, time final awakening, and SOL to calculate sleep duration. Parental sleep diaries yield valid estimates compared with actigraphy such as sleep onset and wake-up time (Sadeh, 2008; Werner et al., 2008). However, the agreement of parental estimates of SOL with objective sleep measures has not been studied extensively. In our study, SOL was not an outcome measure and was only used to estimate sleep duration by subtracting SOL from time in bed (TIB). Although most parents are roughly aware of how long it usually takes for their children to fall asleep, there is some bias to underestimate SOL. Consequently, parental diaries provide a somewhat overestimated determination of sleep duration (Dayyat, Spruyt, Molfese, & Gozal, 2011). The systematic nature of the bias makes it possible to obtain an unbiased parental estimate of sleep duration by means of a simple subtraction (Nelson et al., 2014). Importantly, such a correction would not impact the estimated slopes of our regression analyses and, therefore, would not change our conclusions. Indeed, reanalysis including sleep duration without SOL (time lights out – time final awaking) did not yield different results.

Second, the lack of objective sleep assessments by means of EEG or actigraphy made it impossible to evaluate other sleep variables that have been shown to relate to cognitive performance as well, including sleep efficiency (Astill et al., 2012), fragmentation, and regularity of sleep–wake patterns (Oosterman, Van Someren, Vogels, Van Harten, & Scherder, 2009). Another limitation is that the study was observational rather than experimental. Nevertheless, various sleep durations were reported in our sample of typically developing children aged 9 to 11 years, and the average sleep duration of 9:54 (SD = 0:33) was comparable to that reported in other studies including children of this age range (Iglowstein et al., 2003; Laberge et al., 2001; Szymczak et al., 1993). Compared with the sleep curves of Iglowstein and colleagues (2003), 14% of the children in our study scored below the 25th percentile (indicating that they belong to the 25% shortest sleepers given their age, which compares with approximately half an hour sleep restriction per day) and 36% scored above the 75th percentile (longest sleepers), which is half an hour longer than the average for that age. However, this variation of sleep duration may have heterogeneous origins. Where short sleep often signifies a deficiency in sleep duration (through sleep problems, inappropriate bedtimes, etc.), it is likely that in some of the short-sleeping children sleep duration is sufficient. Thus, the current effect estimates are likely to be more conservative than studies employing experimental manipulation of sleep length or studies on a sample including sleep-deprived children would have revealed.

The major finding of the current study was that the association between sleep duration and cognitive performance in children varies with different temperament traits. Among children with high levels of negative affectivity or introverted children, the longer sleepers perform worse on tasks for sustained attention and working memory. The findings have major implications for future research. First, temperament is an important factor to include in future research on sleep and cognition in children. Second, investigating the brain structural and functional correlates of these temperament traits may help in understanding the effects of sleep on cognition in children. Third, future studies may profit from the inclusion of physiological measures of tonic or task-related arousal to gain more insight into the actual role of arousal on the sleep–temperament–performance association. Although our findings should be interpreted with caution, they provide a novel perspective in the field and warrant further exploration in future studies.

Of note, we do not infer that partial sleep deprivation should be applied in introverted and negatively affective children. Studies have reported detrimental effects of short sleep in children, including more internalizing and externalizing behavioral problems (Astill et al., 2012; Sadeh et al., 2002) and an increased risk of obesity (Cappuccio et al., 2008). It remains to be evaluated whether these detrimental effects are outweighed by possible advantages of setting limits to the sleep duration of introverted children and children with high negative affectivity.

Acknowledgments

The authors thank all of the schools and families for their participation and all of the students who helped in collecting the data. This work was supported by the Netherlands Organization of Scientific Research (NWO), The Hague: National Initiative Brain and Cognition Research Program "Innovative Learning Materials and Methods" under Grant 056-32-013 and VICI Innovation Grant 453-07-001.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jecp.2015.11.014.

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