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Sleep during infancy, inhibitory control and working memory in toddlers: findings from the FinnBrain cohort study

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Abstract

Background: Sleep difficulties are associated with impaired executive functions (EFs) in school-aged children. However, much less is known about how sleep during infancy relates to EF in infants and toddlers. The aim of this study was to investigate whether parent-reported sleep patterns at 6 and 12 months were associated with their inhibitory control (IC) and working memory (WM) performances at 30 months.

Methods: This study included children whose parents filled in a sleep questionnaire at 6 or 12 months and who participated in the development assessment at 30 months (initial available sample at 30 months; $N = 472$). The final sample comprised (a) 359 infants with IC task and sleep questionnaire at 6 months and 322 toddlers at 12 months and (b) 364 infants with WM task and sleep questionnaire at 6 months and 327 toddlers at 12 months. Nighttime, daytime and total sleep duration, frequency of night awakenings, time awake at night, and proportion of daytime sleep were assessed at 6 and 12 months using the Brief Infant Sleep Questionnaire. IC at 30 months was measured using a modified version of the Snack Delay task, and WM was measured at 30 months using the Spin the Pots task. Further, children were divided into three groups (i.e., "poor sleepers", "intermediate sleepers", and "good sleepers") based on percentile cut-offs (i.e., <10th, 10th–90th and > 90th percentiles) to obtain a comprehensive understanding of the direction and nature of the associations between sleep and EF in early childhood.

Results: Our results showed an inverted U-shaped association between proportion of daytime sleep at 12 months and IC at 30 months, indicating that average proportions of daytime sleep were longitudinally associated with better IC performance. Furthermore, a linear relation between time awake at night at 12 months and WM at 30 months was found, with more time awake at night associating with worse WM.

Conclusions: Our findings support the hypothesis that sleep disruption in early childhood is associated with the development of later EF and suggest that various sleep difficulties at 12 months distinctively affect WM and IC in toddlers, possibly in a nonlinear manner.

Keywords: Sleep, Inhibitory control, Working memory, Infancy, Toddlers

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Introduction

The first years of life are characterized by rapid brain growth and development (Choe et al. 2013; Knickmeyer et al. 2008). These processes are considered connected to the development of sleep, which is one of the primary activities of the brain in young children (Dahl 1996). The most rapid development in sleep organization takes place during the first 6 months of life, followed by smaller changes that occur later (de Weerd and van den Bossche 2003; Henderson et al. 2011).

Adequate sleep is essential for the maintenance of optimal cognitive and emotional functioning, especially in childhood (Astill et al. 2012; Mindell et al. 2011). Of these, executive functions (EFs) are particularly sensitive to the effects of childhood sleep problems (Turnbull et al. 2013), with neuroimaging evidence in young adults suggesting that sleep loss affects the frontal lobes more than it does other areas of the brain (Cajochen et al. 2001; Finelli et al. 2000; Thomas et al. 2000). Sleep difficulties (e.g., insufficient sleep or frequent night awakening) are associated with worse performance in EF tasks in school-aged children (Astill et al. 2012; Sadeh et al. 2002). More specifically, objective sleep measures such as lower actigraph-based sleep efficiency and longer sleep latency are associated with worse performance in working memory (WM) tasks at all load levels in school-aged children, whereas shorter actigraph-based sleep duration is associated with lower performance in WM tasks at the highest load level only (Steenari et al. 2003). Similar associations have been reported between parental reports of increasing sleep problem severity and lower verbal WM scores in school-aged children (Cho et al. 2015). Furthermore, comparable findings have been also described in earlier stages of childhood. For instance, maternal-reported insufficient sleep in early school age years (ages 5–7 years) and preschoolers (ages 3–4 years) has been related to poorer mother- and teacher-reported ranges of neurobehavioral processes in middle childhood, including a general measure of EF (Taveras et al. 2017). Finally, in preschoolers, short actigraph-based sleep duration at night has been related to a greater number of impulsive errors on a computerized go/no-go test in 3–5 year old children, indicating poor inhibitory control (IC; Lam et al. 2011).

Despite evidence supporting the foundation of EF during infancy (i.e., the maturation of networks related to EF and the many EF skills that emerge during the first years of life; Diamond 2006; Grossmann 2013), studies examining the associations between sleep and EF outcomes in infants and/or toddlers are limited, with most evidence of this association being reported from studies of preschool and school-aged children. To our knowledge, only four (mostly small) studies have longitudinally examined the associations between sleep quality and domains of EF in early childhood. The four studies can be summarized as follows: Bernier et al. (2010) found a greater proportion of parent-reported night sleep at both 12 and 18 months was associated with better IC performance at 26 months of age, and Bernier et al. (2013) found the same occurred at the age of 4. Sadeh et al. (2015) found lower actigraph-based sleep quality in 12-month-old infants predicted preschoolers' worse executive attentional control. Finally, Makela et al. (2019) found infants with a high frequency of parent-reported signalled night awakenings at 8 months performed worse in a computerized EF task (but not in IC or WM tasks) at 24 months of age.

The importance of further investigating the significance of early sleep is highlighted by the small number of previous studies conducted in young children, the small sample sizes used in these previous studies, the large variability observed in sleep quality and its rapid development in early childhood, and the lack of studies pertaining to multiple forms of sleep disturbances in young children. Furthermore, most of the previous studies have reported the effects of disturbed sleep, but very few studies have examined the opposite extreme (i.e., characteristics of "good sleep") and/or the intermediate levels of the sleep distribution. Recent studies indicate that sleep duration at both extremes in school-aged children (Chaput et al. 2016) and toddlers (Kocevska et al. 2017) is associated with negative health-related outcomes, whereas average sleep duration levels are related to better outcomes, indicating the existence of an inverted U-shaped pattern, rather than a linear association. Therefore, further studies should consider both good and intermediate levels of sleep quality to determine the degrees to which they differentially associate with EF. Examining the effects of these three early sleep-quality categories (i.e., poor, intermediate, and good) on EF in infancy and toddlerhood could lead to a novel understanding of the roles that different dimensions of infant sleep play in toddlers' EF development.

To address the gaps in the previous literature, the objectives of this study were to investigate whether parent-reported sleep quality and/or duration in infants at 6 and 12 months are associated with EF, more specifically IC and WM performance, at 30 months, in a large sample of young children. Based on the existing literature on infants (Bernier et al. 2010), we hypothesized that a higher proportion of daytime sleep during the first year of life is associated with lower IC performance at the age of 30 months. Second, we hypothesized that shorter nighttime sleep is associated with lower performance in both IC and WM tasks due to the previously reported cross-sectional associations between shorter nighttime sleep duration and poorer IC and WM in school-aged children (Cho et al. 2015; Lam et al. 2011). Third, we hypothesized that a greater number of night awakenings is related to lower IC performance because higher frequency of night awakenings has been associated with difficulties in behavioural inhibition in school-aged children (Sadeh et al. 2002). Finally, in addition to children with possible sleep problems (i.e., "the poor sleepers"), we also separately considered cases of the opposite extreme (i.e., "the good sleepers") as well as those in between both extremes (i.e., "the intermediate sleepers"). To do this, we created the cut-offs for the three sleep groups, which were defined as short, intermediate, and long, based on the <10th, 10th–90th, and > 90th percentiles, which are similar to the recommended sleep duration criteria suggested by the National Sleep Foundation (Hirshkowitz et al., 2015). Further, 90th and 10th percentiles are suggested to represent useful cut-offs for screening clinically significant cases (Paavonen et al. 2020). To our knowledge, the relevance of the infants' "good sleep" and toddlers' "intermediate sleep" in EF performance has not yet been investigated.

Materials and methods

Participants

The data are part of the larger FinnBrain Birth Cohort Study (www.finnbrain.fi; Karlsson et al. 2018), which comprises consecutive women at gestational week 12 receiving free ultrasounds at Turku University Hospital, Finland; their children-to-be-born; and fathers of the children/partners of the mothers ($N = 3808$ mothers and $N = 2623$ fathers). The subsample in this study included children who had participated in the development assessment at 30 months of age and whose parents had reported their children' sleep at 6 or 12 months. Altogether, 472 children participated in the developmental assessment of the FinnBrain Child Development and Parental Functioning Lab in the research site of the University of Turku at 30 months of age (Karlsson et al. 2018). Two researchers (i.e., clinical psychologists and/or advanced psychology students) carried out the 1.5-h visits. From all children participating in EF task assessments, 47 (9.96%) children in the IC task and 42 (8.90%)

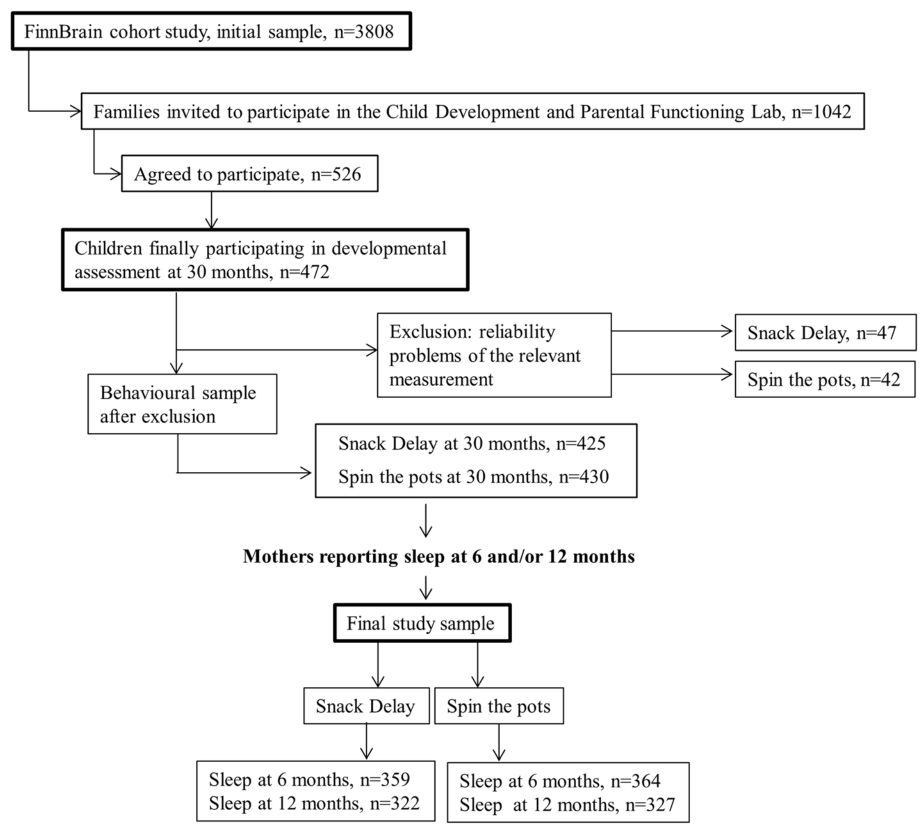

Fig. 1 Flowchart of sampling procedure and exclusion criteria. This figure shows how the final sample for this study was selected. Initially, 472 children participated in the developmental assessment and from them, 47 children in Snack Delay and 42 children in Spin the Pots were excluded from the final analyses due to reliability problems of the relevant measurement. Furthermore, only those children of the remaining sample whose mothers reported on sleep at 6 and/or12 months were included in the final analyses, resulting in the following samples: i) for IC task, 359 infants with sleep questionnaire at 6 months and 322 with sleep questionnaire at 12 months; and ii) for WM task at 30 months, 364 infants with sleep questionnaire at 6 months and 327 with sleep questionnaire at 12 months

in the WM task were excluded due to reliability problems of the relevant measurement (e.g., administrator mistake or a child was too restless or unable to concentrate). Furthermore, only those children of the remaining 425/430 (90.04/91.10%) sample whose mothers reported on sleep at 6 and/or 12 months were included in the final analyses, resulting in the following samples: (a) for the IC task, 359 infants with sleep questionnaire at 6 months and 322 with sleep questionnaire at 12 months; and (b) for WM task at 30 months, 364 infants with sleep questionnaire at 6 months and 327 with sleep questionnaire at 12 months. Of those, 336 children had complete sleep-measure information at both time points and in both EF tasks. We included a flowchart of the study sampling procedure (Fig. 1).

Measures

Key variables

Sleep questionnaire Parents' perceptions of their infants' sleep and sleep problems at 6 and 12 months were assessed using the Brief Infant Sleep Questionnaire, which was filled in by the mothers (Sadeh 2004). The questionnaire includes 13 items that measure parents' perceptions of their children's sleep during the prior week. The Brief Infant Sleep Questionnaire has been validated against actigraphy and sleep diaries and has demonstrated high test–retest reliability (Sadeh 2004). Based on previous literature, the variables of interest were (a) nighttime sleep duration, (b) daytime sleep duration, (c) frequency of night awakenings per night, and (d) time

Table 1 Sociodemographic, cognitive and sleep variables at 6 and 12 months

Sociodemographic variables, categorical			
	N (%)		
Gender (girls/boys)	166 (45.9) / 196 (54.1)		
Birth order (first/other)	183 (52.1) / 168 (47.9)		
Maternal education level, pregnancy (primary/secondary/higher)	81 (23.1) / 113 (32.2) / 157 (44.7)		
Sociodemographic variables, continuous			
	Mean (SD)	*Min*	*Max*
Child's age at 30 months of EF assessment, days	917.13 (13.75)	883.00	986.00
Gestational age at birth, weeks	39.81 (1.52)	31.86	42.43
Maternal age when baby born, years	31.04 (4.28)	19.00	42.00
Infant birth weight, kg	3.57 (0.50)	1.47	5.47
Infant birth height, cm	50.62 (2.23)	39.00	57.00
Number of siblings	0.74 (0.87)	0.00	5.00
Cognitive variables, at 30 months			
INTER-NDA Mean Cognitive Score	3.57 (0.32)	1.92	4.00
Snack Delay, total score	27.91 (8.27)	0.00	36.00
Spin the Pots, total score	11.99 (3.53)	3.00	16.00
Sleep variables at 6 months			
BISQ nighttime sleep duration, hours	9.87 (1.17)	1.00	12.00
BISQ daytime time sleep duration, hours	3.82 (1.29)	1.50	11.00
BISQ total sleep duration, hours	13.66 (1.50)	5.50	18.50
BISQ proportion daytime sleep, %	27.48 (7.66)	12.00	81.82
BISQ number of awakenings / night	2.41 (1.60)	0.00	11.00
BISQ time awake / night, hours	0.44 (0.44)	0.00	2.00
Sleep variables at 12 months			
BISQ nighttime sleep duration, hours	10.26 (0.98)	4.00	13.00
BISQ daytime time sleep duration, hours	2.61 (1.17)	1.00	11.00
BISQ total sleep duration, hours	12.75 (1.02)	7.00	16.00
BISQ proportion daytime sleep, %	19.64 (5.40)	8.00	38.00
BISQ number of awakenings / night	1.85 (1.36)	0.00	8.00
BISQ time awake / night, hours	0.32 (0.52)	0.00	5.00

INTER-NDA INTERGROWTH-21st Neurodevelopmental Assessment, *BISQ* Brief Infant Sleep Questionnaire, *SD* Standard deviation awake at night. Each of these items is open-ended. In addition, two additional sleep variables were created for the purpose of this study: (e) total sleep duration per 24 h (nighttime sleep duration + daytime sleep duration) and (f) proportion of daytime sleep (daytime sleep/total sleep duration per 24 h × 100). Finally, all the sleep variables were categorized into three groups, where the cut-offs were set at <10th, 10th–90th, and > 90th percentiles at 6 and 12 months.

Executive functioning (IC and WM) At 30 months, two EF tasks were used: modified Snack Delay (Kochanska et al. 2000) to measure IC and Spin the Pots (Hughes and Ensor 2005) to measure WM.

In the Snack Delay task, the children were seated at a table and asked to place their hands on a mat depicting pictures of hands. The snacks (M&Ms. or raisins according to the parent's choice) were placed under a cup and each child was told he or she could eat the snack when the experimenter rang a bell. Six trials with delays ranging from 10 s to 60 s were conducted. During the trials, the experimenter picked up the bell without ringing it once or twice times before actually ringing the bell after the specified delay. Scores for each trial range from 0 to 4 (0 = *child eats the snack before the bell was raised*, 1 = *child eats the snack after the bell was raised but before it was rung*, 2 = *child touches the cup or the bell before the bell is raised*, 3 = *child touches the cup or the bell after the bell is raised*, 4 = *child waits after the bell has rung*). Additionally, children were given up to 2 extra points based on whether they were able to keep their hands on the mat during the trials. The maximum score in the task is 36, with higher scores indicating better IC (Spinrad et al. 2007).

In the Spin the Pots task, six distinct stickers were hidden under eight visually distinct boxes that were placed on a rotating tray. In each trial, the children were allowed to choose one box and search for the sticker. After each trial, the tray was covered by an opaque scarf and was rotated 180°. The task terminated when children found all hidden stickers or when the maximum number of 16 spins was reached. Final score was calculated as the number of trials minus the number of unsuccessful attempts to find a sticker, the maximum score being 16 and a higher score reflecting better WM performance.

Other measures

Cognitive functioning at 30 months The INTERGROWTH-21st Neurodevelopmental Assessment (INTER-NDA) is a novel, comprehensive assessment of cognition, language, behaviour, and fine and gross motor skills for children aged 22 to 30 months designed for administration in high-, middle-, and low-income settings

Table 2 Frequencies of each sleep category at 6 and 12 months

	6 months		12 months		*P value**
	Cut-offs 10th, 10-90th, 90th	*N (%)*	Cut-offs 10th, 10-90th, 90th	*N (%)*	
Nighttime sleep duration	Short (≤8.50 h)	39 (12.4)	Short (< 9 h)	42 (14.9)	< 0.001
	Intermediate (8.51-11 h)	196 (62.2)	Medium (9.01–11)	142 (50.5)	0.098
	Long (> 11 h)	80 (25.4)	Long (> 11)	97 (34.5)	< 0.001
Daytime sleep duration	Short (≤2.25 h)	50 (15.8)	Short (≤1.50 h)	29 (10.1)	< 0.001
	Intermediate (2.26–5.33 h)	233 (73.5)	Medium (1.51–3.50 h)	211 (73.8)	0.428
	Long (> 5.33 h)	34 (10.7)	Long (> 3.50 h)	46 (16.1)	0.009
Total sleep duration per 24 h	Short (≤12 h)	46 (14.6)	Short (≤11 h)	34 (12.5)	0.006
	Intermediate (12.01–15.30 h)	235 (74.6)	Medium (11.01-14 h)	204 (73.1)	0.351
	Long (> 15.30 h)	34 (10.8)	Long (> 14 h)	40 (14.3)	0.010
% daytime sleep duration / total sleep	Low (≤18.52%)	33 (10.5)	Low (≤13%)	31 (11.1)	0.174
	Intermediate (18.53–36%)	248 (78.7)	Medium (13.01–27%)	224 (80.3)	0.202
	High (> 36%)	34 (10.8)	High (> 27.01%)	24 (8.6)	0.008
Frequency of night awakenings	Low (≤0.5times)	33 (10.6)	Low (≤0times)	31 (11.3)	0.165
	Intermediate (0.6-4times)	245 (78.5)	Medium (0.1–3.50times)	216 (78.5)	< 0.001
	High (>4times)	34 (10.9)	High (> 3.50times)	28 (10.2)	0.004
Time awake at night	Short (≤0 h)	51 (16.9)	Short (≤0.01 h)	28 (11.0)	< 0.001
	Intermediate (0.01–0.75 h)	214 (71.1)	Medium (0.02–0.83 h)	186 (73.2)	0.031
	Long (> 0.75 h)	36 (12.0)	Long (> 0.83 h)	40 (15.7)	0.027

We created the cut-offs based on the 10th, 10-90th and 90th percentiles; these cut-offs follow the National Sleep Foundation's sleep duration recommendations (Hirshkowitz et al., 2015)

*Chi-square test was used to examine the difference in the proportions at 6 months compared to 12 months, for each of the sleep categories. Here only the *p* values are presented and across populations and languages (Villar et al. 2019). Its 37 items are administered in approximately 15 min using a combination of neuropsychological techniques (Fernandes et al. 2014). Children's performance is scored on a 5-point scale, where higher scores reflect better performance for all domains except for negative and global behaviour. The INTER-NDA has been validated against the Bayley Scales of Infant Development (3rd edition; Murray et al. 2018) and has been shown to have good test–retest reliability (k = 0.79, 95% CI: 0.48–0.96) and inter-rater reliability (k = 0.70, 95% CI: 0.47–0.88; Fernandes et al. 2014). For this study, we used the INTER-NDA mean cognitive score in our analysis because it bears closer relation to EF than motor and language domains do. Further, sleep and cognition are closely related (Deak and Stickgold, 2010).

Sociodemographic measures Additionally, we collected information about the following background variables due to their effects on sleep and EF: (a) children's variables: age at the 30-month visit (in days), sex (1 = girls; 2 = boys), gestational age (in weeks), and birth weight (in kilograms); (b) maternal variables: educational level during pregnancy (i.e., 1 = secondary education or lower, 2 = tertiary vocational education, 3 = university degree), maternal age when baby was born (in years), and parity during pregnancy (i.e., 1 = first vs 2 = others). Most of these data were obtained from the Medical Birth Register kept by the National Institute for Health and Welfare (www.thl.fi; age, sex, gestational age, birth weight, and maternal age, all at the time when the baby was born) or by maternal self-report (level of education and parity

Table 3 Correlations between sociodemographic measures, and sleep at 6 and 12 months, and executive function at 30 months[a]

	Child's age at 30-month	Child's sex	Parity	Gestational age	Birth weight	INTER-NDA mean cognitive score	Maternal educational level	Maternal age when baby born
	r (p)	F (p)	F (p)	r (p)	r (p)	r (p)	F (p)	r (p)
Nighttime sleep duration at 6 mo	**0.11 (0.044)***	0.22 (0.640)	0.78 (0.377)	0.04 (0.418)	−0.01 (0.855)	0.02 (0.683)	0.68 (0.509)	−0.10 (0.054)
Nighttime sleep duration at 12 mo	−0.06 (0.268)	0.10 (0.750)	0.27 (0.603)	**0.12 (0.019)***	0.03 (0.523)	−0.00 (0.948)	2.77 (0.064)	**0.13 (0.015)***
Daytime time sleep duration at 6 mo	0.04 (0.462)	1.56 (0.212)	**8.42 (0.004)****	−0.03 (0.578)	0.09 (0.058)	−0.03 (0.581)	0.03 (0.966)	0.04 (0.398)
Daytime time sleep duration at 12 mo	0.01 (0.849)	1.06 (0.305)	0.01 (0.923)	0.03 (0.499)	0.02 (0.673)	−0.02 (0.730)	0.18 (0.839)	0.03 (0.591)
Total sleep duration at 6 mo	0.10 (0.064)	0.00 (0.947)	**9.38 (0.002)****	0.02 (0.768)	0.09 (0.059)	−0.03 (0.589)	0.70 (0.495)	−0.08 (0.100)
Total sleep duration at 12 mo	−0.09 (0.119)	2.84 (0.093)	0.00 (0.990)	**0.14 (0.007)****	0.09 (0.072)	−0.04 (0.402)	**3.22 (0.041)***	−0.10 (0.049)
Proportion daytime sleep at 6 mo	−0.04 (0.479)	0.84 (0.359)	3.55 (0.060)	−0.04 (0.429)	0.09 (0.060)	−0.04 (0.405)	0.14 (0.873)	0.02 (0.692)
Proportion daytime sleep at 12 mo	0.03 (0.627)	1.42 (0.234)	0.31 (0.579)	−0.04 (0.433)	0.05 (0.319)	−0.04 (0.464)	0.27 (0.760)	0.05 (0.198)
Number of awakenings/night at 6 mo	0.06 (0.284)	**4.47 (0.035)***	0.01 (0.913)	−0.07 (0.156)	−0.08 (0.096)	− 0.01 (0.877)	2.02 (0.134)	0.03 (0.481)
Number of awakenings/night at 12 mo	−0.00 (0.975)	0.53 (0.466)	0.08 (0.780)	**−0.13 (0.012)***	−0.08 (0.138)	− 0.07 (0.179)	2.95 (0.054)	**0.15 (0.004)****
Time awake / night at 6 mo	**0.16 (0.004)****	0.58 (0.448)	1.24 (0.265)	−0.03 (0.580)	−0.00 (0.941)	− 0.04 (0.454)	0.78 (0.457)	**0.15 (0.004)****
Time awake / night at 12 mo	0.02 (0.748)	0.02 (0.876)	0.30 (0.586)	−0.05 (0.406)	−0.05 (0.246)	0.00 (0.995)	1.29 (0.278)	0.04 (0.493)
Snack Delay, Hands version, 30 mo[b]	0.03 (0.549)	**11.99(0.001)*****	0.36 (0.550)	0.03 (0.475)	0.03 (0.579)	0.08 (0.104)	1.39 (0.249)	−0.05 (0.355)
Spin the Pots at 30 mo[b]	**0.15 (0.003)****	**7.75 (0.006)****	0.24 (0.626)	**0.18(< 0.001)*****	0.06 (0.191)	**0.10 (0.033)***	**3.08 (0.047)***	0.01 (0.860)

mo Months
*p value < 0.050
**p value < 0.010
**p value ≤0.001
[a]For the correlation analyses, the continuous values of each of the sleep variables were used (i.e., total score). Pearson correlations (r) were used for all the covariates, except for maternal educational level, child's sex and parity where ANOVA test (F) was applied
[b]Correlation between Snack Delay, Hands version and Spin the Pots: r = 0.239, $p < 0.001$

assessed at gestational week 14 as part of a larger set of questionnaires).

Statistical analyses

Statistical analyses were performed with SPSS Statistics V25.0. Descriptive statistics were conducted to obtain means, standard deviations, frequencies, and percentages of the variables of interest. Total scores of both EF tasks were negatively skewed. Therefore, we normalized these scores using logarithm transformation. After this, the transformed scores appeared normally distributed, with all skewness values being between − 0.5 and 0.5, indicating the distribution is approximately symmetric. First, Pearson correlations (for continuous variables) and analysis of variance (ANOVA) test (for categorical and dichotomous variables) between our key variables (sleep and EF measures) and other variables of interest (INTER-NDA cognitive score, child sex, age and birth weight at 30-month visit, gestational age, parity, and maternal education and age when infants were born) were conducted. We did this to define potential covariates used in subsequent analyses. Second, to examine the association of sleep with IC (Snack Delay) and WM (Spin the Pots), the sleep variables (nighttime sleep duration, daytime sleep duration, total sleep duration per 24 h, proportion of daytime sleep, number of night awakenings per night, and time awake at night) were categorized into three groups, where the cutoffs were set at <10th, 10th–90th, and > 90th percentiles at 6 and 12 months.

To compare EF in these groups, we used ANOVA tests. The first model was an unadjusted model. In the final adjusted model, covariates that were first selected on theoretical bases and then significantly correlated with any of the two outcomes were included (gestational age, maternal education, age at 30 months, child's sex, and INTER-NDA mean cognitive score at 30 months).

Table 4 The differences between sleep category at 6 months and 12 months in predicting child inhibitory control at 30 months

6 months					
	10th pc	**10-90th pc**	**90th pc**	**Unadjusted model**	**Adjusted model**
	Mean (SD)[a]	**Mean (SD)[a]**	**Mean (SD)[a]**	**Statistics[b]**	**Statistics[c]**
Night sleep duration	28.63 (8.94)	27.62 (8.38)	28.19 (8.27)	$F(2,317) = 0.416$, $p = 0.660$, $\eta^2 = 0.003$	$F(7,306) = 0.675$, $p = 0.510$, $\eta^2 = 0.004$
Day sleep duration	27.62 (8.89)	27.79 (8.31)	28.84 (8.22)	$F(2,319) = 0.486$, $p = 0.616$, $\eta^2 = 0.003$	$F(7,308) = 0.630$, $p = 0.533$, $\eta^2 = 0.004$
Total sleep duration	26.82 (9.68)	27.97 (8.22)	28.64 (7.92)	$F(2,317) = 0.403$, $p = 0.669$, $\eta^2 = 0.003$	$F(7,306) = 0.095$, $p = 0.910$, $\eta^2 = 0.001$
% daytime sleep	28.23 (8.77)	27.51 (8.48)	30.34 (6.99)	$F(2,317) = 2.614$, $p = 0.075$, $\eta^2 = 0.016$	$F(7,306) = 2.271$, $p = 0.089$, $\eta^2 = 0.015$
Night awakenings	24.80 (9.96)	28.02 (8.38)	29.03 (6.60)	$F(2,314) = 1.576$, $p = 0.208$, $\eta^2 = 0.010$	$F(7,303) = 2.196$, $p = 0.113$, $\eta^2 = 0.014$
Time awake / night	26.18 (9.55)	28.19 (8.28)	27.47 (8.83)	$F(2,302) = 1.375$, $p = 0.254$, $\eta^2 = 0.009$	$F(7,292) = 1.193$, $p = 0.305$, $\eta^2 = 0.008$
12 months					
	10th pc	**10-90th pc**	**90th pc**	**Unadjusted model**	**Adjusted model**
	Mean[a]	**Mean[a]**	**Mean[a]**	**Statistics[b]**	**Statistics[c]**
Night sleep duration	28.24 (8.98)	27.94 (8.50)	27.90 (8.03)	$F(2,282) = 0.230$, $p = 0.794$, $\eta^2 = 0.002$	$F(7,272) = 0.329$, $p = 0.720$, $\eta^2 = 0.002$
Day sleep duration	26.44 (9.39)	28.59 (7.62)	26.09 (11.02)	$F(2,287) = 1.131$, $p = 0.324$, $\eta^2 = 0.008$	$F(7,277) = 0.986$, $p = 0.374$, $\eta^2 = 0.007$
Total sleep duration	28.92 (8.06)	28.04 (8.07)	27.09 (10.04)	$F(2,280) = 0.591$, $p = 0.554$, $\eta^2 = 0.004$	$F(5,277) = 0.765$, $p = 0.466$, $\eta^2 = 0.005$
% daytime sleep	24.62 (9.86)	28.70 (7.63)	25.32 (11.26)	$F(2,280) = 3.003$, $p = 0.051$, $\eta^2 = 0.021$	$\mathbf{F(7,271) = 3.012}$, $\boldsymbol{p = 0.039}$, $\boldsymbol{\eta^2 = 0.022}$*
Night awakenings	29.15 (7.53)	27.70 (8.92)	28.93 (6.71)	$F(2,276) = 1.392$, $p = 0.876$, $\eta^2 = 0.001$	$F(7,268) = 0.068$, $p = 0.934$, $\eta^2 = 0.001$
Time awake / night	29.42 (7.36)	28.07 (8.53)	28.46 (7.14)	$F(2,253) = 0.443$, $p = 0.643$, $\eta^2 = 0.003$	$F(7,245) = 0.294$, $p = 0.746$ $\eta^2 = 0.002$

Similar associations were obtained with non-transformed outcomes
**p* value> 0.050; η^2=eta squared (i.e. measure of effect size in ANOVA)
[a]Mean and standard deviation (SD) of each group, in each of the sleep variables, are obtained from the raw outcome measure
[b]Unadjusted model: No covariates
[c]Adjusted model: gestational age, maternal education, age at 30 months, child's sex and INTER-NDA mean cognitive score at 30 months

Separate analyses were conducted for sleep at 6 and 12 months because sleep patterns notably differ from 6 to 12 months and thus their specific effects might vary. Tukey honestly significant difference (HSD) post hoc test was used to evaluate significant mean differences between groups. This test was selected because it is less conservative than other, more rigorous methods, such as Bonferroni post hoc test, which tends to provide false negative results (Kim 2015). To avoid this, we chose Tukey HSD for this study.

Results

Sociodemographic, cognitive, and sleep variables

The sociodemographic, cognitive, and sleep variables are presented in Table 1. The frequency distributions of the sleep groups at each time point (6 and 12 months) are shown in Table 2. Correlations between the potential covariates with EF and sleep variables appear in Table 3.

Sleep at 6 and 12 months and IC at 30 months

In the first ANOVA, we did not find significant associations between sleep at 6 and 12 months and IC at 30 months, although the proportion of daytime sleep at both 6 and 12 months was an almost significant predictor of IC: $F\ (2,\ 317) = 2.614$, $p = 0.075$, $^{2} = 0.016$; and $F\ (2,\ 280) = 3.003$, $p = 0.051$, $^{2} = 0.021$, respectively. However, when we controlled for cognitive level and other potential confounding factors (i.e., gestational age, maternal education, age at 30 months, and child's sex) in the adjusted model, the proportion of daytime sleep at 12 months reached statistical significance, $F\ (7,\ 271) = 3.012$, $p = 0.039$, $\eta^2 = 0.022$. More specifically, the post hoc tests showed that 12-month-old infants with smaller proportion of daytime sleep (10th percentile) had worse IC functioning at 30 months than infants with average proportion of daytime sleep did at the age of 12 months (10th–90th percentile; $p = 0.048$; see Table 4 for all statistical values in IC).

Sleep at 6 and 12 months and WM at 30 months

In the first ANOVA, in which no covariates were included, we found significant differences in WM according to nighttime sleep duration at 6 months, $F(2,\ 347) = 3.626$, $p = 0.028$, $\eta^2 = 0.020$. The post hoc test showed that infants with longer sleep duration at night (90th percentile) performed better than the infants with short sleep duration at night did (≤10th percentile; $p = 0.015$) as well as better than infants with normal ranges of nighttime sleep duration did (10th–90th percentile; $p = 0.036$). However, this association did not remain significant when we controlled for the covariates (Table 5).

In addition, time awake at night at 12 months was associated with WM performance, $F(2,\ 282) = 5.002$, $p = 0.007$, $\eta^2 = 0.034$. The post hoc test showed that 12-

Table 5 The differences between sleep category at 6 months and 12 months in predicting child working memory at 30 months

	10th pc	10-90th pc	90th pc	Unadjusted model	Adjusted model
6 months					
	Mean (SD)[a]	**Mean (SD)[a]**	**Mean (SD)[a]**	**Statistics[b]**	**Statistics[c]**
Night sleep duration	11.15 (4.12)	11.81 (3.39)	12.39 (3.66)	F(2,347) = 3.626, *p* = 0.028, $\eta^2 = 0.020$	F(7,334) = 2.019, *p* = 0.134, $\eta^2 = 0.012$
Day sleep duration	12.58 (3.18)	11.83 (3.59)	11.06 (3.78)	F(2,348) = 1.747 *p* = 0.176, $\eta^2 = 0.010$	F(7,335) = 1.495, *p* = 0.226, $\eta^2 = 0.009$
Total sleep duration	12.00 (3.66)	11.90 (3.55)	11.75 (3.47)	F(2,346) = 0.068, p = 0.934 $\eta^2 = 0.000$	F(7,333) = 0.298, *p* = 0.742, $\eta^2 = 0.002$
% daytime sleep	12.33 (3.60)	11.94 (3.46)	11.06 (4.11)	F(2,346) = 1.142, *p* = 0.320, $\eta^2 = 0.007$	F(7,333) = 0.822, *p* = 0.440, $\eta^2 = 0.005$
Night awakenings	10.91 (4.09)	11.91 (3.58)	12.33 (2.82)	F(2,342) = 0.477, *p* = 0.621, $\eta^2 = 0.003$	F(7,329) = 0.963, *p* = 0.383, $\eta^2 = 0.006$
Time awake / night	11.22 (3.50)	12.28 (3.23)	11.12 (4.19)	F(2,332) = 1.534, *p* = 0.217, $\eta^2 = 0.009$	F(7,320) = 1.879, *p* = 0.154, $\eta^2 = 0.012$
12 months					
	10th pc	**10-90th pc**	**90th pc**	**Unadjusted model**	**Adjusted model**
	Mean[a]	**Mean[a]**	**Mean[a]**	**Statistics[b]**	**Statistics[c]**
Night sleep duration	11.39 (4.03)	12.30 (3.22)	11.70 (3.57)	F(2,310) = 0.572, *p* = 0.565, $\eta^2 = 0.004$	F(7,298) = 0.972, *p* = 0.379, $\eta^2 = 0.006$
Day sleep duration	11.71 (3.87)	12.16 (3.46)	11.31 (3.98)	F(2,316) = 1.113, *p* = 0.330, $\eta^2 = 0.007$	F(7,304) = 1.123, *p* = 0.327, $\eta^2 = 0.007$
Total sleep duration	12.29 (3.58)	12.02 (3.56)	11.33 (3.70)	F(2,308) = 0.898, *p* = 0.409, $\eta^2 = 0.006$	F(7,297) = 2.020, *p* = 0.135, $\eta^2 = 0.013$
% daytime sleep	11.69 (3.72)	12.12 (3.49)	10.88 (4.07)	F(2,308) = 1.565, *p* = 0.211, $\eta^2 = 0.010$	F(7,297) = 2.075, *p* = 0.127, $\eta^2 = 0.014$
Night awakenings	12.82 (3.24)	11.91 (3.69)	11.61 (3.08)	F(2,304) = 2.038, *p* = 0.132, $\eta^2 = 0.013$	F(7,294) = 1.283, *p* = 0.279, $\eta^2 = 0.009$
Time awake / night	12.91 (3.05)	12.00 (3.60)	10.32 (3.82)	**F(2,282) = 5.002, p = 0.007, $\eta^2 = 0.034$**	**F(7,271) = 4.731, p = 0.014, $\eta^2 = 0.031$***

Similar associations were obtained with non-transformed outcomes

*p value> 0.050; η^2=eta squared (i.e. measure of effect size in ANOVA)

[a]Mean and standard deviation (SD) of each group, in each of the sleep variables, are obtained from the raw outcome measure

[b]Unadjusted model: No covariates

[c]Adjusted model: gestational age, maternal education, age at 30 months, child's sex and INTER-NDA mean cognitive score at 30 months

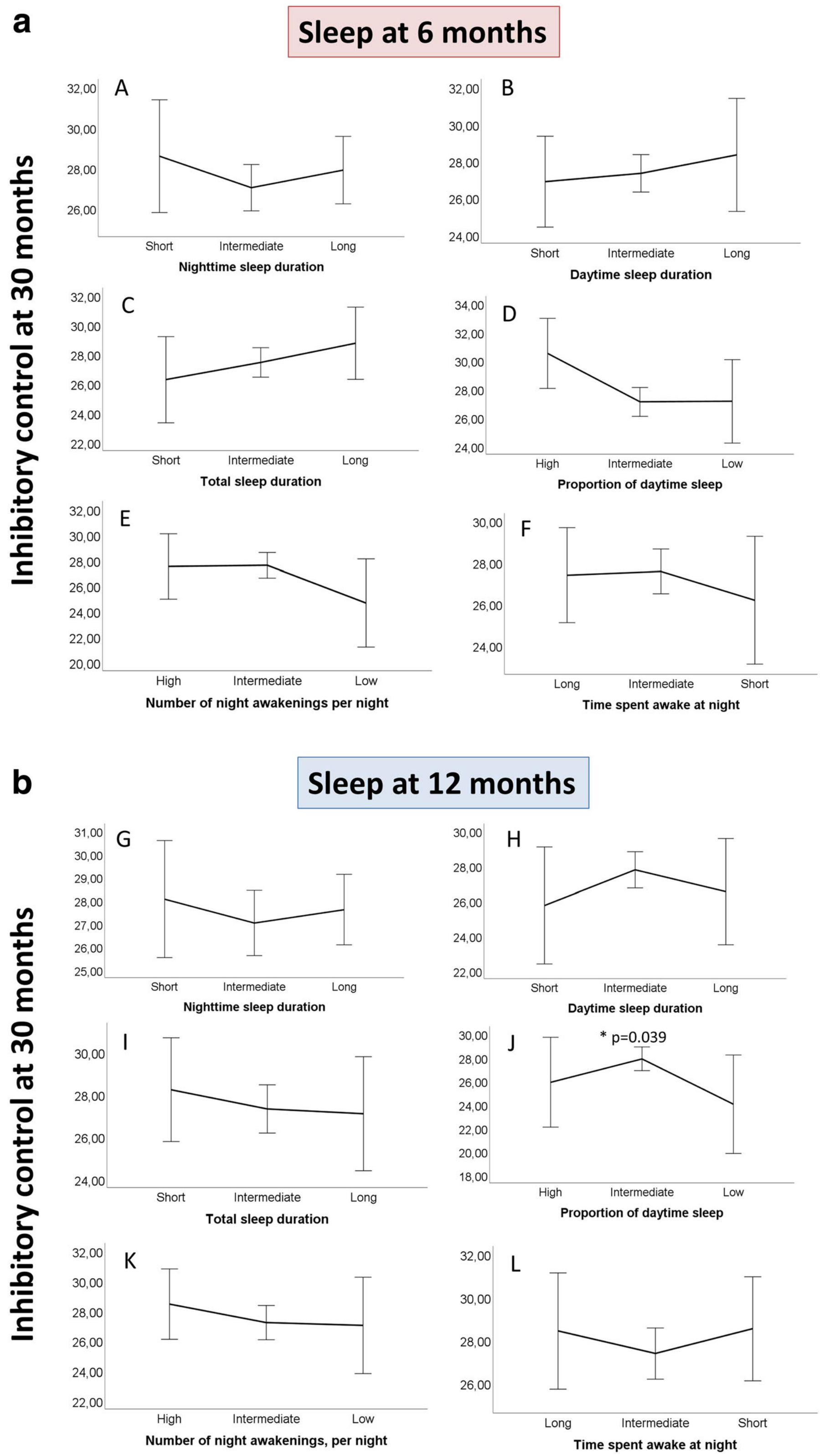

Fig. 2 (See legend on next page.)

(See figure on previous page.)

Fig. 2 a Estimated Marginal Means for Snack Delay, Hands version task at 30 months, for each sleep group at 6 months. This graph represents the Estimated Marginal Means for Inhibitory control at 30 months, for each sleep variable based on the 10th, 10-90th and 90th percentiles, at 6 months. Y axis represents the estimated marginal means for the inhibitory control measure at 30 months and X axis the three sleep groups. Error bars represent the 95% Confidence Interval. The sleep variables represented here are: nighttime sleep duration (A), daytime sleep duration (B), total sleep duration (C), proportion of daytime sleep (D), number of night awakenings per night (E) and time awake during night (F). At 6 months, we can observe a clear linear association between total sleep duration (C) and IC, while a clear inverted U-shaped association was found between nighttime sleep duration (A) and IC. Finally, a trend towards an existing U-shaped association was found in daytime sleep duration (B) and proportion of daytime sleep (D), and towards and inverted U-shaped association in number of night awakenings (E) and time awake at night (F). **b** Estimated Marginal Means for Snack Delay, Hands version task at 30 months, for each sleep group at 12 months. This graph represents the Estimated Marginal Means for Inhibitory control at 30 months, for each sleep variable based on the 10th, 10-90th and 90th percentiles, at 12 months. Y axis represents the estimated marginal means for the inhibitory control measure at 30 months and X axis the three sleep groups. Error bars represent the 95% Confidence Interval. The sleep variables represented here are: nighttime sleep duration (G), daytime sleep duration (H), total sleep duration (I), proportion of daytime sleep (J), number of night awakenings per night (K) and time awake during night (L). At 12 months, a linear association between total sleep duration (I) and IC was found. Inverted U-shaped associations were reported in daytime sleep duration (H) and proportion of daytime sleep (J), while a trend towards U-shaped relation was found in nighttime sleep duration (G), number of night awakenings (K) and time awake at night (L)

month-old infants who spent a long time awake at night (≥90th percentile) performed worse in the WM task than 12-month-old infants who slept through the night did (≤10th percentile; $p = 0.002$) as well as worse than those infants who spent an average amount of time awake at night did (10th–90th percentile; $p = 0.011$). In the adjusted model (Table 4b), we found this association remained significant when controlling for the covariates, $F(7, 271) = 4.731$, $p = 0.014$, $\eta^2 = 0.031$. The group differences also remained similar in the post hoc tests; that is, the infants who spent less time awake (≤10th percentile) had better performance in WM tasks than infants who spent more time awake (≥90th percentile) did: $p = 0.005$; as well as infants who spent an average amount of time awake (10th–90th percentile) did: $p = 0.028$.

The estimated marginal means for WM and IC at 30 months and for each sleep group at 6 and 12 months are displayed in Fig. 2a and b (IC) and Fig. 3a and b (WM).

ANOVA tests were also conducted with nontransformed outcomes, and interestingly, similar results were observed. For this reason, and for the purpose of this study, we report only the results with the transformed outcomes.

Discussion

In this longitudinal birth cohort study, we show that (a) the proportion of daytime sleep at 12 months and IC at 30 months follows an inverted U-shaped relation and that (b) the association between time spent awake at night at 12 months and WM at 30 months is linear. By longitudinally examining the associations between infant sleep and toddler EF across the range of infant sleep outcomes (i.e., not only in infants with sleep problems but also in those who might be labelled "good sleepers" and "intermediate sleepers"), these findings extend the current understanding of the relationship between infant sleep and toddler EF and provide novel evidence to support a dose-dependent curvilinear relationship between sleep and EF during early childhood.

Consistent with our first hypothesis and with a previous longitudinal study in infants (Bernier et al. 2010), we found the proportion of daytime sleep at 12 months was associated with IC at 30 months. Although our finding of the inverted U-shaped association between proportion of daytime sleep and IC is novel, previous cross-sectional studies with toddlers (Kocevska et al. 2017), children (Chaput et al. 2016), and adults (Leng et al. 2015) have suggested sleep duration at both extremes is associated with negative health-related outcomes. This finding is also consistent with evidence from neuroendocrine literature, which reports inverted U-shaped associations between cortisol levels and cognition in both children (Jager et al. 2014) and adults (Schilling et al. 2013). Taken together, these findings and ours suggest nonlinear patterns of association may describe the relationship between complex biological processes during early childhood more accurately than linear associations do. Furthermore, daytime sleep time seems to be mostly determined by maturation (i.e., age; Paavonen et al. 2020; Weissbluth 1995), and most of the infants sleep an average of 2 h during daytime. Interestingly, one recent longitudinal study reported that inappropriate amounts of daytime sleep were related to worse quality of nighttime sleep in 3 to 8-month-old infants (Paavonen et al. 2019). Therefore, it is likely that infants with average amounts of daytime sleep most likely represent the normal ranges of the developmental stage in other areas of development, such as cognition or self-regulation.

We did not find evidence to support our second hypothesis that shorter nighttime sleep would be associated with lower performance in both IC and WM tasks. Such associations have been reported in two cross-sectional studies conducted in school-aged children (Cho et al. 2015; Lam et al. 2011). Our failure to confirm these previous findings could be explained by the fact

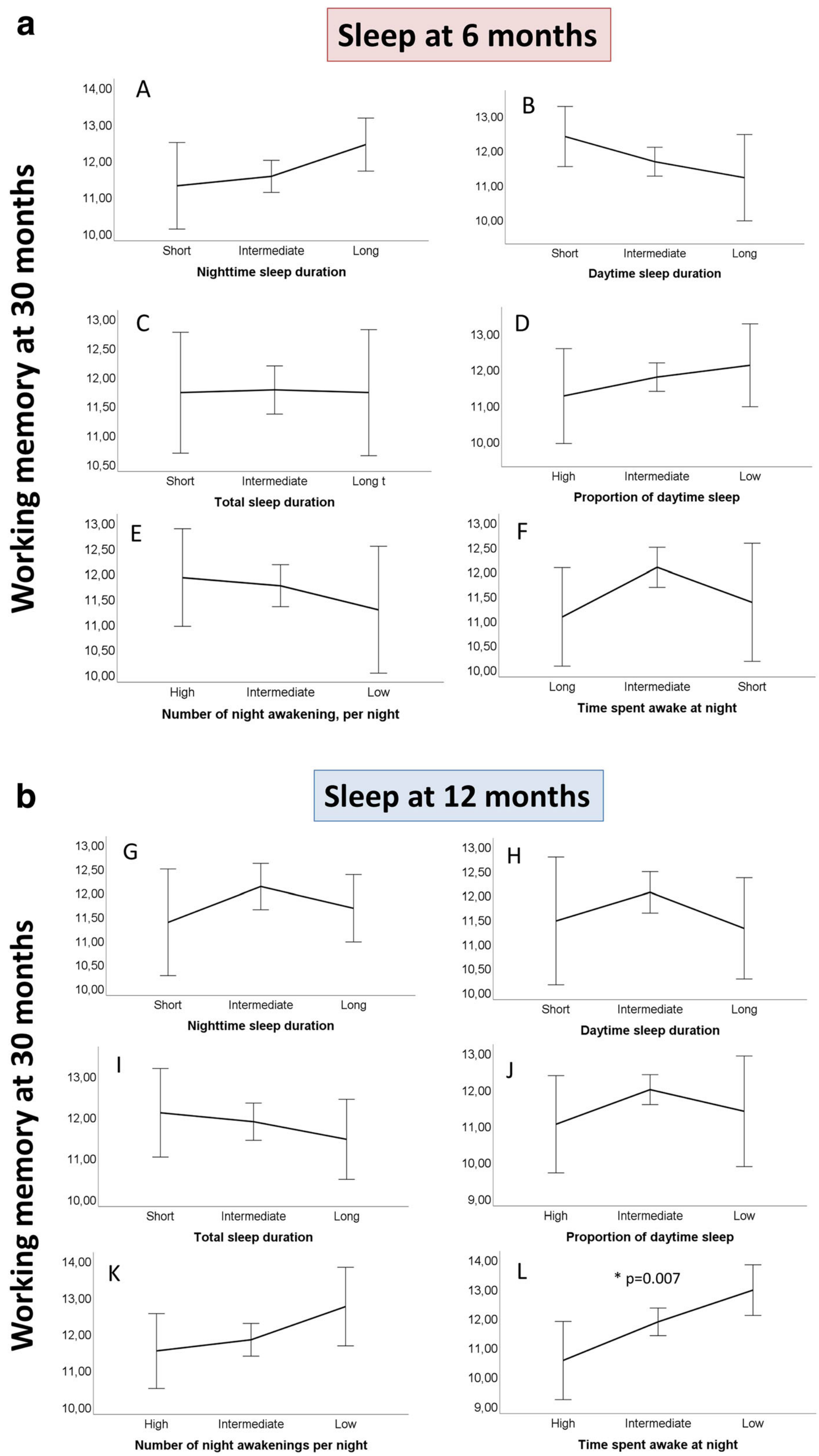

Fig. 3 (See legend on next page.)

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Fig. 3 a Estimated Marginal Means for Spin the Pots task at 30 months, for each sleep group at 6 months. This graph represents the Estimated Marginal Means for Working Memory at 30 months, for each sleep variable based on the 10th, 10-90th and 90th percentiles, at 6 months). Y axis represents the estimated marginal means for the working memory measure at 30 months and X axis the three sleep groups. Error bars represent the 95% Confidence Interval. The sleep variables represented here are: nighttime sleep duration (A), daytime sleep duration (B), total sleep duration (C), proportion of daytime sleep (D), number of night awakenings per night (E) and time awake during night (F). At 6 months we can observe that almost all the relations between sleep and WM are linear (A-E), while an inverted U-shaped association between time spent awake at night (F) and WM was reported. **b** Estimated Marginal Means for Spin the Pots task at 30 months, for each sleep group at 12 months. This graph represents the Estimated Marginal Means for Working Memory at 30 months, for each sleep variable based on the 10th, 10-90th and 90th percentiles, at 12 months). Y axis represents the estimated marginal means for the working memory measure at 30 months and X axis the three sleep groups. Error bars represent the 95% Confidence Interval. The sleep variables represented here are: nighttime sleep duration (G), daytime sleep duration (H), total sleep duration (I), proportion of daytime sleep (J), number of night awakenings per night (K) and time awake during night (L). At 12 months, linear associations were only found in total sleep duration (I) and time awake at night (L), with a tendency towards linearity in number of night awakenings (K). The associations between nighttime sleep duration (G), daytime sleep duration (H) and proportion of daytime sleep duration (J) with WM at 30 months follow an inverted U-shaped association

that significant sleep deprivation might be quite uncommon in infants among whom sleep is strongly driven by homeostatic pressure (Jenni and LeBourgeois 2006). Finally, we should take into account that some research supports the notion that EF in early childhood may be best described by a single factor, rather than by different aspects (Espy et al. 2011; Shing et al. 2010; Wiebe et al. 2008), because EF undergoes rapid development in infancy and the subdomains of EF are highly interrelated at these early stages (Diamond 2013).

Our third hypothesis was partially confirmed because although we did not find significant associations between the number of night awakenings and IC at 30 months, we did find that time spent awake at night at 12 months was longitudinally associated with WM performance at 30 months in a linear manner. This suggests night awakenings are often normative in infants' development, whereas long periods spent awake at night more likely indicate a deviance in sleep quality in early childhood. The number of night awakenings tends to remain stable during the first year of life, ranging from 0 to 3.4 episodes per night for very young infants (0–2 months) to 0 to 2.5 per night at the age of 12–24 months (Galland et al. 2012). Therefore, time spent awake at night might be a better indicator of disturbed sleep than the number of night awakenings is, and thus time spent awake at night could be more harmful for the development of some EFs, such as WM. Further studies on the effects of sleep fragmentation (i.e., frequency of night awakening and time spent awake at night) on the development of EF deficits are still needed. To the best of our knowledge, our study is the first to report an association between parent-reported time spent awake at night and EF in this age group.

Finally, it should be noted that the lack of association between the number of night awakenings and EF could be related to the use of parent-reported sleep measures in this study. For instance, although infants may briefly wake up during the night, many of them are able to fall back to sleep by themselves, and thus very short awakenings are not necessarily noticed by their parents (Minde et al. 1993). Therefore, the use of more objective sleep measures, such as actigraphy, may be useful to measure the exact frequency of night awakenings. Furthermore, night awakenings are more frequent and more normative in infancy than they are later during development and, hence, they may have distinct effects on IC performance in older children.

Interestingly, our findings concerning sleep during the first year of life and EF (i.e., IC and WM) at the age of 30 months were only observed when sleep was measured at the age of 12 months, while there were no associations between sleep at 6 months and EF at 30 months. One possible explanation could be that the high interindividual variability in sleep quality, which is mainly seen during the first 6 months of life, could be related to environmental factors that temporarily impair sleep in infants (Ednick et al. 2009). Therefore, the effects that sleep at 6 months exert on later development in toddlers might be less robust. However, recent findings from our group using a different sample showed that parental reported short sleep duration at 3, 8, and 18 months was longitudinally associated with attention difficulties at the age of 5 (Huhdanpaa et al. 2019). Nevertheless, the cognitive measures used in this previous study and our current study were different (i.e., parent-reported vs behavioural cognitive measures, respectively), and thus the results are not directly comparable.

Overall, our findings support the hypothesis that sleep disruption in early childhood is longitudinally associated with later EF and that different sleep patterns in 12-month-old infants affect distinct aspects of EF (i.e., IC and WM) at the age of 30 months. Considering that EF and its associated neural circuitry experience rapid development between the ages of 2 and 5 (Best and Miller 2010) and that sleep plays a vital restorative role in brain functioning (Medic et al. 2017), disrupted sleep early in development could have negative longitudinal consequences for the development of EF. The findings of our study suggest that variation in sleep quality more clearly influences the variation in EF when sleep is measured at the age of 12 months compared to 6 months. At the age of 12 months, the most relevant sleep quality patterns from the perspective of toddlers' WM and IC are the measures related to the acquisition of the circadian rhythm (i.e., proportion of daytime sleep and time awake at night).

The main strength of our study is the large sample size and the longitudinal design, which captures the long-term consequences of early childhood sleep disturbances on IC and WM in toddlers. Moreover, we measured sleep at 6 and 12 months, which enabled us to examine the effects of sleep in very early stages of life. Furthermore, the study is population-based, and we were able to account for various confounding variables, including maternal factors and child cognitive development at 30 months. Another major strength of this study is the approach of using three different sleep groups ("good sleepers", "intermediate sleepers", and "bad sleepers") to study the nonlinear associations between sleep and EF.

Our study has some limitations. First, sleep measures were only reported using parental reports, and we did not use objective measures, such as actigraphy. Although parental reports and objective reports may disagree in some cases (Molfese et al. 2015), sleep reports are still considered valid for assessing sleep in young children. Moreover, use of parental reports enables the collection of larger samples. Second, our sample was composed of relatively healthy mothers and infants; thus, generalization of the results should be made cautiously with respect to clinical populations. Third, no adjustment for current sleep at 30 months was available in this study, which may result in less accurate findings.

Conclusions

The main findings of our study show that the association between the proportion of daytime sleep at 12 months and IC at 30 months follows an inverted U-shape, whereas a linear relation between time awake at night at 12 months and WM at 30 months was found. However, no significant associations between sleep at 6 months and any of the EF measures at 30 months were found, reflecting the high inter-individual variability in sleep development occurring at this early stage of life. According to our results, it seems that different sleep difficulties at 12 months affect different aspects of EF (i.e., IC and WM) at 30 months, and these associations follow different patterns. Further studies should include the measure of time awake at night in addition to night awakening frequency to obtain a better understanding of the effects that fragmented sleep might have on the development of WM in later stages of life. Finally, rather than assuming only a longer proportion of daytime sleep has adverse effects on IC, daytime sleep proportion at both extremes and the intermediate levels should be considered in future studies of EF development. If toddlers' EF aspects, such as IC and WM, are improved by treating specific sleep difficulties early in infancy, this would be highly relevant for the improvement of children's cognitive functioning.

Abbreviations

ANOVA: Analysis of variance.; EF: Executive functioning.; IC: Inhibitory control.; INTER-NDA: INTERGROWTH-21st Neurodevelopment Assessment.; WM: Working memory.

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Authors' contributions
IMM conceptualized, analysed and wrote the original draft of the manuscript. SN conducted the behavioural testing, and assisted in the data analyses. TM assisted in the data analyses. EE conducted the behavioural testing. RR and MF conceptualized the study. HK conceptualized the study and provided funding. EJP conceptualized, supervised and provided funding for the study. LK conceptualized, supervised and provided funding for the study. All authors read, reviewed, edited and approved the final manuscript.

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Availability of data and materials

Due to Finnish federal legislation on personal data protection in medical research, the original research data cannot be made available online, but data can potentially be shared with Material Transfer Agreement. Requests and collaboration initiatives can be directed to the Board of FinnBrain Birth Cohort Study. Please contact Hasse Karlsson (hasse.karlsson@utu.fi) or Linnea Karlsson (linnea.karlsson@utu.fi).

Declarations

Ethics approval and consent to participate

The parents gave written informed consent on their own and on their child's behalf. The study was approved by the Ethical Committee of the Southwestern Finland Hospital District (number 57/180/2011).

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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