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Carolin Konrad
Ruhr-Universitat Bochum

Jane S. Herbert
University of Sheffield, herbertj@uow.edu.au

Silvia Schneider
Ruhr-Universitat Bochum

Sabine Seehagen
Ruhr-Universitat Bochum

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Abstract

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Keywords

sleep, night's, imitation, prior, infant, between, relationship, measures

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The relationship between prior night's sleep and measures of infant imitation

Carolin Konrad[1], Jane S. Herbert[2], Silvia Schneider[1] & Sabine Seehagen[1]

[1] Ruhr-Universität Bochum, Bochum, Germany

[2] University of Sheffield, Sheffield, UK

Corresponding author:

Carolin Konrad

Ruhr-Universität Bochum

Department of Psychology

Massenbergstr. 9-13

44787 Bochum

Germany

Phone: +49 (0)234 32 23128

Email: carolin.konrad@rub.de, J.S.Herbert@sheffield.ac.uk, silvia.schneider@rub.de, sabine.seehagen@rub.de

Abstract: We examined whether sleep quality during the night and naps during the day preceding a learning event are related to memory encoding in human infants. Twenty-four 6- and twenty-four 12-month-old infants' natural sleeping behavior was monitored for 24 hours using actigraphy. After the recording period, encoding was assessed using an imitation paradigm. In an initial baseline phase, infants were allowed to interact with the stimulus to assess spontaneous production of any target actions. Infants then watched an experimenter demonstrate a sequence of three target actions and were immediately given the opportunity to reproduce the demonstrated target actions to assess memory encoding. Analyses revealed significant correlations between nighttime sleep quality variables (sleep efficiency, sleep fragmentation) and immediate imitation in 6-month-olds, but not in 12-month-olds. High sleep quality in the preceding night was positively associated with next day's memory encoding in 6-month-old infants.

Keywords: infancy, sleep, encoding, memory, learning, imitation, actigraphy

"If sleep does not serve an absolutely vital function, then it is the biggest mistake the evolutionary process ever made."

Allan Rechtschaffen, 1978

University of Chicago Sleep Laboratory

In older children and adults, sleep is crucial for cognitive functioning, particularly for a multitude of memory processes (Diekelmann & Born, 2010; Rasch & Born, 2013). Sleep enhances both the quantity and quality of declarative and non-declarative memories, and facilitates the application of existing knowledge to new situations (e.g., Ellenbogen, Hu, Payne, Titone, & Walker, 2007; Gais & Born, 2004; Wagner, Gais, Haider, Verleger, & Born, 2004). Although it has been proposed that sleep may be particularly important during periods of enhanced plasticity (such as adolescence; Dahl, 2004; Dahl & Spear, 2004), surprisingly little research has focused on the effects of sleep on cognitive functioning in infancy (for a discussion, see El-Sheikh & Sadeh, 2015). Two recent empirical studies have shown that sleeping is associated with strengthened declarative memory consolidation in 6- and 12-month-olds (Seehagen, Konrad, Herbert, & Schneider, 2015) and semantic generalization in 9- to 16-month-old infants (Friedrich, Wilhelm, Born, & Friederici, 2015). However, the relation between infant sleep and the learning process, memory encoding, has yet to be explored. In addition, although young infants spend the majority of their time asleep, sleeping behavior rapidly changes throughout the first year of life and there are large inter-individual as well as intra-individual day-to-day differences in sleeping patterns (Acebo et al., 2005; Galland, Taylor, Elder, & Herbison, 2012; Goodlin-Jones, Burnham, Gaylor, & Anders, 2001; Hoppenbrouwers, Hodgman, Arakawa, Geidel, & Sterman, 1988; Scher, Epstein, & Tirosh, 2004). Thus, in the present study we assessed whether sleep quantity and quality prior to a learning event is related to subsequent memory encoding in 6- and 12-month-old infants.

So far, research exploring the relations between infant sleep and general cognitive development has focused on habitual sleep (e.g., Freudigman & Thoman, 1993; Gibson, Elder, & Gander, 2012; Scher, 2005). Habitual sleep is a measure of how the infant usually sleeps and is defined by sleep data that is averaged over several nights (often 5-7) for each individual infant. Sleep data is typically collected via parent completed sleep logs/diaries, or with objective techniques (e.g., actigraphy, polysomnography; for review of method strengths and limitations see Sadeh, 2015). In these studies, cognitive development is often assessed with the Mental Scale of the Bayley Scales of Infant Development (Bayley, 1993). The Bayley Scales provides a global score of general cognitive functioning and has been used to show normal sleep development is associated with favorable cognitive development (Ednick et al., 2009).

A handful of studies have also specifically considered which facets of *sleep quality* might be related to higher levels of general cognitive development in infancy (Ednick et al., 2009; Freudigman & Thoman, 1993). One indicator of sleep quality found to be positively associated with cognitive development is sleep efficiency (Gibson et al., 2012; Scher, 2005). Sleep efficiency is defined as the percentage of time spent asleep within the total sleep period (i.e., time the infant is put to bed until final wake up), and there is a temporal increase in sleep efficiency during the first year of life (De Marcas, Soffer-Dudek, Dollberg, Bar-Haim, & Sadeh, 2015). Another indicator of sleep quality is sleep fragmentation, which can be measured through the number or duration of night wakings. Number of night wakings, for example, has been found to be negatively related to the cognitive scores on the Bayley Scales (Scher, 2005). Total sleep duration per se is not an indicator of sleep quality in infants (Sadeh, 2015) and seems unrelated to their cognitive development at a given age (Bernier, Carlson, Bordeleau, & Carrier, 2010; Scher, 2005). However, sleep duration can be regarded as a marker of maturation as with increasing age infants spend less time asleep and more of their sleep time occurs at night relative to the day (Bernier et al., 2010; Gibson et al., 2012;

Scher, 2005). Thus, age and developmental status of an infant are related to their sleeping behavior (Acebo et al., 2005).

The Bayley Scales only provides a global score of general cognitive functioning and are thus not suitable for exploring relations between sleep and specific memory processes. The only infant study which has assessed the relation between habitual sleep and specific memory processes, rather than general cognitive development, used an elicited imitation paradigm (Lukowski & Milojevich, 2013). In this paradigm, infants are first allowed to explore the stimuli in a baseline control phase that is child-controlled rather than fixed in duration. A series of target actions are then modeled to the infant and the infant is presented with the stimuli again immediately and/or after a delay and is prompted verbally to imitate the actions (Bauer, 1996). Imitation tasks can provide a measure of the amount of information encoded into memory, and also the structure of the memory, by examining how many actions are reproduced by the infant and whether the actions are produced in the same order as they were shown. In Lukowski and Milojevich's (2013) sample of 10-month-old infants, the duration of daytime napping was positively associated with encoding of the correct temporal order of target actions but not with the total number of actions encoded. The percentage of sleep in 24 hours that was obtained at night was negatively associated with the correct temporal order. The authors suggested that habitual napping might be especially important for encoding of the correct temporal order of actions. In that study, habitual sleep was assessed using a parental-report questionnaire regarding their infants' sleeping behavior averaged over the past week (Brief Infant Sleep Questionnaire (BISQ), Sadeh, 2004). Since parents systematically underestimate the frequency and duration of night wakings in their infants (Sadeh, 2008; Werner, Molinari, Guyer, & Jenni, 2008), it remains unclear whether any associations between sleep fragmentation and infant imitation might be detected when sleep is assessed objectively.

A further unanswered question relates to the role of night sleep immediately preceding a learning event. On the one hand, research on sleep inertia (i.e., “the transitional state of lowered arousal occurring immediately after awakening from sleep”, Tassi & Muzet, 2000, p. 341) in adults indicates that prior sleep can lead to a diminished learning performance up to four hours after sleep occurred (Tassi & Muzet, 2000). On the other hand, sleep deprivation studies with adults show that sufficient sleep is essential for encoding (e.g., Harrison & Horne, 2000) and recent studies indicate that prior sleep can also have *enhancing* effects on subsequent encoding (Antonenko, Diekelmann, Olsen, Born, & Mölle, 2013; Mander, Santhanam, Saletin, & Walker, 2011). For example, adults who are well rested exhibit better encoding of episodic memories than adults in a sleep deprivation condition who had not slept for one night before the encoding session (Yoo, Hu, Gujar, Jolesz, & Walker, 2007). In children, some studies have examined the effect of night sleep restriction on cognitive functioning (Carskadon, Harvey, & Dement, 1981; Kopasz et al., 2010; Könen, Dirk, & Schmiedek, 2015; Randazzo, Muehlbach, Schweitzer, & Walsh, 1998; Sadeh, 2007). Sleep restriction negatively affects encoding in children, particularly in tasks that tap into higher-order cognitive processes such as creative thinking (Randazzo et al., 1998). In contrast, at least mild sleep restriction does not influence encoding ability of lower cognitive tasks, such as learning of short word lists (Biggs et al., 2010).

Only one study has so far examined the effect of prior daytime naps on the encoding of novel actions in infants (Seehagen et al., 2015). In this study, 6- and 12-month-old infants were randomly assigned to either take or to not take a naturally-occurring extended nap within 4 hours preceding participation in an imitation task (Barr, Dowden, & Hayne, 1996). Sleeping behavior was monitored using actigraphy. In the imitation task, a within-subject procedure was used such that infants first participated in a baseline phase during which they interacted with the stimuli for 90 s to assess spontaneous production of any target actions. Then, the experimenter modeled three target actions. In the test phase immediately afterwards, the infants were allowed to interact with the stimuli again to assess encoding of the target actions. Infants in both the nap and in the no-nap condition produced a significantly higher number of target actions in the test phase than in the baseline phase and this increase did not differ between the two conditions. Thus, infants in the nap and in the no-nap condition encoded the target actions equally well.

In Seehagen et al. (2015), only the effect of daytime sleep during the 4 hours preceding a learning event was measured. Previous research in adults and children has shown that night sleep might be especially important for subsequent encoding (Gomez, Newman-Smith, Breslin, & Bootzin, 2011; Walker, 2009). Therefore, in the present study we focused on the association between infants' sleep during the night and subsequent memory encoding. The primary question of interest was whether there was a relation in 6- and 12-month-old infants between their sleep quality in the preceding night and their encoding performance. We were interested in investigating two different age-groups as there are complex relations between sleep and cognitive functioning such that specific findings obtained with one age-group can often not be generalized to different developmental periods (Ednick et al., 2009). Using an objective technique to monitor sleep behavior (i.e., actigraphy) for 24-hours, we assessed the role of prior sleep/wakefulness for infants' learning of novel actions in an imitation task, controlling for the infants' overall developmental status, parental education, and breastfeeding. Parental characteristics such as socio-economic status have been shown to be associated with a child's sleeping patterns (Acebo et al., 2005; Zhang, Li, Fok, & Wing, 2010). For example, 12- to 60- month-old infants of parents with a lower socio-economic status (SES) have a higher variability in bed times, spend more time awake at night and rise later in the morning than infants of parents with higher SES (Acebo et al., 2005). Furthermore, breastfeeding is associated with longer night waking episodes, at least in 3-month-old infants (Tikotzky et al., 2015).

We hypothesized that encoding performance would be positively associated with sleep quality (sleep efficiency, sleep fragmentation) of the preceding night. As sleep duration does not seem to be an indicator of sleep quality in infants (Sadeh, 2015), our second hypothesis was that prior night's sleep duration would not be associated with encoding performance on the next day. Third, we predicted that, in accordance with previous findings (Seehagen et al., 2015), there would be no relation between preceding daytime sleep and encoding performance. We made no specific assumptions for differences between age-groups.

Method

Participants

The final sample consisted of twenty-four 6-month-old and twenty-four 12-month-old full-term infants (50% girls). All infants participated within two weeks of turning 6 or 12 months, respectively (6-month-olds: *M* age = 186 days, *SD* = 7 days; 12-month-olds: *M* age = 365 days, *SD* = 8 days). Ten additional infants were tested but excluded from the final sample due to actiwatch failure (*n* = 4), fussiness (*n* = 3), experimenter error (*n* = 2), or refusal to remain seated during the test phase (*n* = 1).

The families were initially recruited from local birth registers from the city of Bochum. Part of the sample derived from a bigger study on sleep-dependent memory in infants (Seehagen et al., 2015). Except for one, all infants were living with both parents. Sixty-seven percent of the infants were first born; the maximum number of siblings an infant had was three. Twelve 6-month-olds and six 12-months-olds were breastfed when they participated in the study; three parents in each age-group did not provide this information. On average, mothers of the 6-month-old infants were 32 (*SD* = 5) years old and had 16 years of education. Fathers were 35 (*SD* = 5) years old on average and had 16 years of education. Mothers of the 12-month-old infants were 34 (*SD* = 4) years old and had 16 years of education. Fathers were 35 (*SD* = 5) years old on average and had 16 years of education; one father did not provide this information.

Measures

Sleep records.

Actigraphy. Sleep was recorded using Micro Motionlogger® Actiwatches (Ambulatory Monitoring inc.). Actiwatches (devices similar in appearance to a wristwatch) record the frequency of movement with the aid of a piezo-electric beam, which produces a voltage each time the actiwatch is moved. Actigraphy is a valid and accurate method for assessing sleep-wake patterns in infants (Müller, Hemmi, Wilhelm, Barr, & Schneider, 2011; Sadeh, Acebo, Seifer, Aytur, & Carskadon, 1995). An algorithm which was specifically developed for the differentiation of sleep and wake states in infants (Sadeh Infant algorithm, Sadeh et al., 1995) was used to calculate for each minute whether the infant was awake or asleep.

Sleep diary. Parents were asked to complete a sleep diary to document their infant's sleeping (i.e., exact nap times, the time they put their infant to bed at night, wake up times at night, and final wake up time in the morning). Additionally, parents noted the exact start and end times of periods when the actiwatch was removed (e.g., while changing diapers) as well as times when the infant was moved externally (e.g., being pushed in a pram). Since actigraphy is exclusively based on motion, the data it produces during periods of external movement can be distorted. During these times, the sleep diary was used to calculate sleep durations.

Stage of development. To control for infants' general development, parents completed a German translation of the Ages and Stages Questionnaire (ASQ, Bricker & Squires, 1999) for infants aged 6 months or 12 months, respectively. The questionnaires contain six questions for each of the following five developmental areas: communication, gross motor, fine motor, problem solving, and personal social. Parents rate on a 3-point scale (yes, sometimes, not yet) whether their infant is able to perform described activities. Infants score 10 points for every activity parents rate with “yes”, 5 points for every activity parents rate with “sometimes”, and 0 points for every activity parents rate with “no”. A score for each developmental domain is calculated by summing up the points from the relevant items. A total score across developmental domains is calculated by summing up the scores from the five domains. The ASQ shows good to acceptable internal consistency, strong two week test-retest reliability and moderate agreement between parent and a trained examiner within developmental areas, as well as concurrent validity (Squires, Twombly, Bricker, & Potter, 2009). The total ASQ-Scores were used in our analyses to control for overall developmental status. In the present sample, the 6-month-olds’ ASQ scores ranged from 115 to 295 (M = 225, SD = 41) and the 12-month-olds’ scores ranged from 165 to 300 (M = 226, SD = 36).

Stimuli. Four different hand puppets were used in the imitation task (counterbalanced across age and gender) which were specifically made for research purposes and not commercially available. The puppet stimuli have been successfully used in a number of deferred imitation studies with 6- and 12- month-old infants (e.g., Barr et al., 1996; Hayne, MacDonald, & Barr, 1997; Brito & Barr, 2014; Seehagen et al., 2015). There were two puppets resembling a mouse and two resembling a rabbit, one of each being grey and one pink. A removable felt mitten matching the color of the puppet was placed over each puppet’s right hand. Only one puppet was used for each infant.

Procedure

All families were visited in their own homes twice, with a 24-hour delay between the sessions. The visits occurred at a convenient time for the parents when the infant was likely to be alert and playful. The time of the visits varied from 8.45 am to 6.15 pm with a mean time of 11.50 am. On the first visit, the experimenter obtained informed consent from the parents and handed out the ASQ and a sleep diary to chart infant’s sleeping behavior. An actiwatch was attached to the infant’s left ankle. On the second visit, the actiwatch was removed, the sleep diaries and ASQ collected, and infants' encoding performance in an imitation task (Barr et al., 1996) was assessed. Each infant received a small gift for participation at the end of the second visit.

Imitation Task. A within-subject design was used in which all infants participated in a baseline, a demonstration, and an immediate test phase during the experimenter's second visit. Throughout the procedure, the infant sat on their parent's lap and the experimenter knelt in front, holding the puppet at the infant's eye level. During the baseline phase, each infant's spontaneous production of the target actions was assessed. Here, each infant was allowed to interact with the puppet for 90 s from first touching the puppet. The experimenter then secured a bell inside the puppet's mitten, while it was outside the infant's view, for the demonstration phase. The puppet was returned to the infant's view and three target actions were demonstrated to the infant: (1) removing the mitten from the puppet's hand, (2) shaking the mitten three times, making the bell ring, and (3) replacing the mitten. This sequence of actions was repeated two more times and lasted a total of approximately 30 s. The test phase followed immediately and the infant was given 90 s from first touching the puppet to reproduce the target actions. The bell inside the mitten was removed before this phase, again outside the infant's view, to avoid prompting memory retrieval (e.g., Barr, Vieira, & Rovee-Collier, 2001; Hayne et al., 1997). The same puppet was used for all phases with each infant, but the puppet was varied across infants. At no time were the puppet or the target actions labeled or described to the infant. Each session was video recorded from the right hand side of the experimenter.

Results

Data Analyses

Video coding. The videotaped baseline and test phases were scored for the presence of any target actions using the program INTERACT (Version 9, Mangold International

GmbH, Arnstorf, Germany). Each infant received an imitation score from 0 to 3 for both the baseline and the test phase. A second independent coder, who was blind to the hypotheses of the study, coded 50% of the videos. Inter-rater reliability was very good, kappa = .91.

Analyses of sleep measures. All analyses of the infant's night sleep (defined as time the infants were put to bed at night until final wake up in the morning) were conducted solely using the actigraphy data. The following actigraphy variables for the night sleep were used for computation: total sleep duration, number of night wakings exceeding 5 minutes, total wake duration, and sleep efficiency (i.e., the percentage of sleep within the total sleep period from the time the infant is put to bed until final wake up). Night wakings are usually defined as period of wakefulness of more than 5 minutes in actigraphy studies with infants since the number of long wake episodes that seriously disrupt sleep are of particular interest (e.g., Sadeh, 1994; Scher & Cohen, 2015; Tikotzky & Shaashua, 2012). Actigraphy records may be somewhat distorted when infants co-sleep with their parents due to the movement of the parents. However, only a minority of infants regularly co-slept around the time of study participation (*n* = 5 six-month-olds and *n* = 4 twelve-month-olds, two caregivers did not provide this information). We did not specifically assess sleeping arrangements during the night preceding the learning event.

For daytime naps during the 24-h recording period, two sleep variables were calculated: number of naps and total nap duration . The times indicated as sleep during the day in the sleep diary were used to identify naps initially. The actigraphy data was used for 68% of all recorded naps to calculate sleep duration. The durations for the remaining naps were extracted from the sleep diary entries as these naps occurred during periods when the infant was moved externally. Additionally, the total sleep duration within 24-hours was calculated.

Preliminary Analyses

There were no differences in maternal and paternal education between age-groups, $t(46) = 0.37$, $p = .710$, and $t(45) = 0.85$, $p = .402$, respectively. Furthermore, the mean ASQ score did not differ between age-groups, $t(46) = -0.15$, $p = .878$.

Sleep parameters. In the 6-month-olds, there were no significant differences in nighttime and daytime sleeping behavior (see Table 1 for sleep variables) between males and females, Wilks' $\lambda = .759$, $F\ (6, 17) = 0.90$, $p = .517$, $\eta_p^2 = .24$, between infants with and without siblings, Wilks' $\lambda = .590$, $F\ (6, 17) = 1.97$, $p = .127$, $\eta_p^2 = .41$, between infants who were or were not breastfed, Wilks' $\lambda = .892$, $F\ (6, 15) = 0.30$, $p = .925$, $\eta_p^2 = .11$, or between infants who regularly did or did not co-sleep with their parents, Wilks' $\lambda = .770$, $F\ (6, 15) = 0.75$, $p = .621$, $\eta_p^2 = .23$.

In the 12-month-olds, there were no significant differences in nighttime and daytime sleeping behavior between males and females, Wilks' $\lambda = .821$, $F\ (6, 17) = 0.62$, $p = .713$, $\eta_p^2 = .18$, between infants with or without siblings, Wilks' $\lambda = .728$, $F\ (6, 17) = 1.06$, $p = .424$, $\eta_p^2 = .27$, or between infants who were or were not breastfed, Wilks' $\lambda = .708$, $F\ (6, 15) = 1.03$, $p = .442$, $\eta_p^2 = .29$. However, a MANOVA revealed a significant multivariate main effect of co-sleeping status on nighttime and daytime sleeping behavior, Wilks' $\lambda = .491$, $F\ (6, 16) = 2.77$, $p = .049$, $\eta_p^2 = .51$. A significant univariate main effect of co-sleeping status was obtained for the number of naps during the 24-h recording period, $F\ (1, 21) = 11.57$, $p = .003$, $\eta_p^2 = .36$, indicating that infants who regularly co-slept with their parents took more naps than infants who did not co-sleep. In addition, a significant univariate main effect of co-sleeping status was obtained for the number of night wakings exceeding 5 minutes, $F\ (1, 21) = 6.17$, $p = .022$, $\eta_p^2 = .23$, indicating that infants who regularly co-slept woke up more often.

Furthermore, 12-month-old infants who co-slept imitated significantly fewer target actions than infants who did not co-sleep, $t(21) = 2.17$, $p = .042$. This was not the case for the 6-month-olds, $t(20) = 0.53$, $p = .603$. Co-sleeping status was thus controlled in further correlations between night sleep variables and adjusted imitation scores for the 12-month-old infants.

Mean starting time of the night sleep period (i.e., when the infant was put to bed) was 08.01 pm for the 6-month-olds and 07.35 pm for the 12-month-olds. Mean wake up time in the morning was 07.14 am for the 6-month-olds and 07.21 am for the 12-month-olds. Sleep measures of infants' sleep within the assessed 24-hours are displayed in Table 1 for each age-group separately. A MANOVA revealed a significant multivariate main effect of age-group on nighttime and daytime sleeping behavior, Wilks' $\lambda = .677$, $F\ (6, 41) = 3.26$, $p = .010$, $\eta_p^2 = .32$. A significant univariate main effect for age-group was obtained for the number of naps , $F\ (1, 46) = 17.34$, $p < .001$, $\eta_p^2 = .27$, indicating that 6-month-old infants took significantly more naps than 12-month-old infants.

---- Insert Table 1 about here ----

Imitation task. There were no significant differences in adjusted imitation scores between males and females at 6 or 12 months, so data was collapsed across gender in the following analyses, $t(22) = -0.30$, $p = .770$, and $t(22) = -1.16$, $p = .260$, respectively. To assess encoding performance, a 2 (Phase: baseline, test) x 2 (Age: 6 months, 12 months) mixed-model ANOVA was conducted. There was a main effect of phase, indicating that infants produced a significantly higher number of target actions during test than during baseline, $F\ (1, 46) = 16.94$, $p < .001$, $\eta_p^2 = .27$ (see Figure 1 for imitation scores). Thus, as a group, infants showed evidence of having encoded the target actions after having watched the demonstration. There was no significant main effect of age and no age x phase interaction effect, biggest $F\ (1, 46) = 0.61$, $p = .440$, $\eta_p^2 = .01$.

Willingness to interact with the puppet and sleep parameters. To assess whether prior sleep was associated with general willingness or interest to interact with the puppet stimuli, we conducted Pearson's correlations between all sleep variables (as shown in Table 1) and the time infants spent touching the puppet during the baseline and the test phase for both age-groups. From these 28 correlations, only one reached significance which we therefore regarded as a chance finding: at 12 months, the time infants touched the puppet during baseline phase was negatively associated with the total duration of naps during the day, $r = -.43$, $p = .038$. Overall, these results therefore suggest that prior sleep was not related to infants' willingness to interact with the stimuli.

---- Insert Figure 1 about here ----

Main Analyses

Prior daytime sleep, total sleep and imitation performance. To relate individual encoding performance to sleep variables, an adjusted imitation score was created by subtracting each infant's baseline score from the infant's imitation score at test (Lukowski & Milojevich, 2013; Sheffield, 2004). The adjusted imitation score could thus range from -3 to +3. In the present sample, it ranged from -1 to 3 in the 6-month-olds and from -2 to 3 in the 12-month-olds.

As expected, number of naps , total sleep duration during the day, and total sleep within 24 hours were not significantly related to the adjusted imitation score at 6 and 12 months, biggest $r = .25$, $p = .245$. Furthermore, time of the visit and length of time the infant had been awake before participating in the imitation task did not significantly correlate with the adjusted imitation score at 6 and 12 months, biggest $r = .19$, $p = .371$.

---- Insert Table 2 about here ----

Prior nighttime sleep and imitation performance. Pearson correlations revealed that sleep quality, but not simply sleep duration at 6 months was associated with encoding performance on the next day (cf. Table 2), confirming our first and second hypotheses. The relations between variables are illustrated in the Figure 2 scatterplots. The longer 6 month old infants had been awake for in the preceding night, the smaller their adjusted imitation score. The more often infants had woken up for more than 5 minutes, the lower their adjusted imitation score. Furthermore, the more efficiently infants slept the night before, the higher their adjusted imitation score. This pattern of results held when excluding the five 6-month-olds who regularly co-sleep with their parents (sleep efficiency: $r = .56$, $p = .020$; time the infant is awake for at night: $r = -.55$, $p = .024$; number of night wakings exceeding 5 minutes: $r = -.47$, $p = .060$). For the 12-month-olds, none of the correlations were significant (see Figure 2) and remained non-significant when excluding the four infants who regularly co-sleep, biggest $r = .27$, $p = .260$.

---- Insert Figure 2 about here ----

Since parental education and developmental status of the infant could be associated with infant encoding performance as well as sleeping behavior (Acebo et al., 2005; Zhang et al., 2010), we tested whether years of maternal and paternal education and the total ASQ score mediated the relation between sleep and adjusted imitation score. When years of maternal and paternal education and the total ASQ score were partialled out, the associations between the adjusted imitation score and sleep quality at 6 months became even stronger (sleep efficiency: $r = .64$, $p = .002$; time the infant is awake for at night: $r = -.63$, $p = .002$; number of night wakings exceeding 5 minutes: $r = -.54$, $p = .011$). Associations remained non significant for the 12-month-old infants, biggest $r = .30$, $p = .212$.

Discussion

The goal of the present study was to examine whether sleeping behavior during the night is related to next day's memory encoding in the first year of life. The results support the hypotheses that sleep quality, but not sleep duration per se, is critical for next day's memory encoding in 6-month-old infants. Hence, having a good night's sleep in the preceding night appears not only to be associated with memory encoding in children and adults (Gomez et al., 2011; Walker, 2009), but already in young infants. The same variables that underlie the relations between habitual sleep quality (i.e., sleep fragmentation and sleep efficiency) and general cognitive development (Gibson et al., 2012; Scher, 2005) appear to be important for the association between immediately preceding night sleep and memory encoding. It is unlikely that these associations can be explained by a third variable such as general developmental status of the infants or socioeconomic background as the associations held when controlling for parent's education and ASQ scores. In addition, sleep quality seems to be the underlying factor for associations with imitation performance: the 12-month-old infants who regularly co-slept with their parents in our sample also showed poorer sleep quality. This might be the reason they had lower imitation scores than infants who did not co-sleep in our sample. The third hypothesis could also be confirmed: in accordance with previous findings (Seehagen et al., 2015) daytime sleep was unrelated to encoding performance.

In Lukowski and Milojevich's (2013) study, habitual sleep in 10-month-olds was only related to more complex aspects in an imitation task like encoding of the temporal order of actions. In the present study we found that, at least in the 6-month-olds, prior sleep was associated with encoding of the number of target actions. Since different measurements of sleep were used between studies (habitual sleep vs. objectively measured prior sleep), it is possible that there are different associations between habitual sleep and prior sleep with encoding.

It might seem surprising that in this sample, the 6- and 12-month-olds only differed significantly in a single sleep variable that is, the number of naps. The literature suggests that while sleep duration in a 24-h period and the nocturnal sleep duration remain relatively constant between 6 and 12 months of age (Iglowstein, Jenni, Molinari, & Largo, 2003; Sadeh, Mindell, Luedtke, & Wiegand, 2009; Scher, Epstein, & Tirosh, 2004; Spruyt et al., 2008), a larger proportion of the total sleep occurs at night by 12 months. In addition, there is a decrease of diurnal sleep (Spruyt et al., 2008). Due to considerable day-to-day variability of sleep, studies examining sleep parameters in infants with objective measures like actigraphy usually take measurements for 5-7 consecutive days and then use the means of these nights to determine the infant's habitual or average sleeping behavior (Sadeh, 2015). As we were especially interested in the effects of such variations in sleep, we only collected sleep data for 24 hours prior to the imitation task. It is thus likely that we did not measure each infant's most representative day of their habitual sleeping behavior. Furthermore, many studies examined sleep quality in large samples using questionnaires to assess sleep (e.g., over 5000 parents in Sadeh et al., 2009; over 2000 parents in Teng, Bartle, Sadeh, & Mindell, 2012). Thus, even differences in sleep variables that were relatively small numerically may have reached statistical significance. In sum, methodological differences to previous studies in sample size, mode of sleep assessment, and length of sampling might explain the lack of age-related differences in sleep parameters in the present study.

What could be the underlying mechanism connecting nighttime sleep quality and next day's encoding performance? The present data are correlational in nature, precluding causal interpretations. Yet, on the basis of experimental research in animals and human adults, it could be speculated that sleep influences encoding performance early in life as well. In previous studies, sleep deprived rats and adults show reduced activity in the hippocampus, a brain region critically involved in learning, during encoding of new information (e.g., Guan, Peng, & Fang, 2004; McDermott et al., 2003; Yoo et al., 2007). Thus, sleep appears to prepare the brain for memory encoding during the next wake phase (Antonenko et al., 2013; Van Der Werf et al., 2009). There are at least two possible hypotheses explaining this function of restoring learning capacities of sleep which are not mutually exclusive and could work hand in hand. The first one, the synaptic homeostasis hypothesis, explains this restoration through the downscaling of synaptic strength during sleep (Tononi & Cirelli, 2006). During wakefulness, synapses become potentiated when new information is encoded (Vyatovskiy, Cirelli, Pfister-Genskow, Faraguna, & Tononi, 2008). Sleep renormalizes synaptic potentiation to a baseline level, saving energy and space in the brain (Tononi & Cirelli, 2014; Vyatovskiy et al., 2008). Thus without sleep, the synapses would soon become saturated and learning capacities would quickly reach a limit during wakefulness (Tononi & Cirelli, 2006, 2014). Hence, it could be speculated that, as a result of synaptic downscaling, the infants in our sample that had better sleep quality in the preceding night showed better learning performance.

A second explanation, the active system consolidation hypothesis, can be derived from the two-stage model of sleep-dependent memory consolidation (Diekelmann & Born, 2010; Frankland & Bontempi, 2005). According to this model, new information is encoded in parallel in hippocampal and cortical networks (Frankland & Bontempi, 2005). The hippocampus allows fast learning and acts as an intermediate buffer which retains information for a limited time. Transfer into cortical networks occurs during sleep when recently acquired information is reactivated in the hippocampal-neocortical network. This "strengthening of cortico-cortical connections eventually allows new memories to become independent of the hippocampus and to be gradually integrated with pre-existing cortical memories" (Frankland & Bontempi, 2005, p. 122). An explanation for the reduced hippocampal activity in sleep-deprived animals and adults can be derived from this model: the previously learned information during wakefulness exceeds the hippocampal encoding capacity and, due to the lack of sleep, the information cannot be consolidated into a long-term store to free up space for new input (Diekelmann & Born, 2010; Frankland & Bontempi, 2005).

Although we did not find an association between night sleep quality and immediate imitation in the 12-month-olds using the puppet task, it is possible that there is an association between sleep quality and encoding at this age in general. Put differently, it seems somewhat unlikely that associations between prior sleep quality and encoding exist in 6-month-old infants as well as older children and adults, but not in 12 month-olds. More comprehensive measures of sleep, like polysomnography, are needed to further investigate the relation between sleep quality and encoding in infants. Polysomnography records body functions during sleep, including electroencephalography to score sleep stages, sleep quality, eye movements, muscle activity, and heart rhythm during sleep. However, complete polysomnography has major disadvantages because it is an expensive procedure that requires the infant to sleep in an unnatural laboratory environment (Sadeh, 2015). Other factors of sleep quality should be considered as well, like disordered breathing during sleep (e.g., snoring). Snoring which can occur frequently in children and can be easily assessed with a one-item screening indicating the frequency of snoring in the child rated by the parents (e.g., Montgomery-Downs, O'Brien, Holbrook, & Gozal, 2004). In addition, more fine-grained analyses of encoding performance could be beneficial. Previous studies showed that there are no differences in imitation performance in the first year of life when tested immediately after the demonstrations (Barr et al., 1996; Herbert, Gross, & Hayne, 2006). In line with that, our sample of 6- and 12-month-olds did not differ in immediate imitation performance even though there are marked age-related changes in memory functioning across the first year of life (Hayne, 2004). Thus, future studies investigating relations between encoding and sleep in infants could benefit from including a wider range of encoding tasks and more comprehensive assessments of sleep quality and architecture.

In a bigger picture, prior sleep could be one factor underlying day-to-day variances in infants' performance in memory tasks. Rapid changes in cooperation, interest, and mood are often an issue when assessing infant memory, especially when tasks involve multiple sessions (Hayne, 2004). Furthermore, in the few studies that assessed test-retest reliabilities for infant memory tasks, there was much variability in performance, leading to reliabilities that were only medium in size (Goertz, Kolling, Frahsek, & Knopf, 2009; Goertz, Kolling, Frahsek, Stanisch, & Knopf, 2008). Thus, it may be informative to collect data about prior sleep to explain variance in performance on a specific day.

The present study shows that prior night sleep is related to memory encoding in young infants. This relation should be investigated further in infants to better understand its importance for cognitive development and to identify its physiological underpinnings.

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Tables

Table 1

	Sleep duration at night in min (*SD*)	Time awake at night in min (*SD*)	Number of night wakings exceeding 5 min (*SD*)	Sleep efficiency in % (*SD*)	Number of naps within 24h (*SD*)	Sleep duration during the day in min (*SD*)	Total sleep duration within 24h in min (*SD*)
6 months	626.8 (81.1)	35.1 (27.7)	1.9 (1.4)	93.2 (4.8)	3.0 (1.2)	130.3 (39.1)	757.1 (77.8)
12 months	657.2 (95.7)	31.2 (24.1)	1.8 (1.4)	93.1 (9.0)	1.8 (0.6)	124.2 (53.7)	781.4 (105.5)
p	.24	.60	.84	.98	.00	.66	.37

Note. *P*-values are provided for the comparison of sleep variables between age-groups.

Table 2

Age-group		Total sleep duration at night (min)	Time awake at night (min)	Number of night wakings exceeding 5 min	Sleep efficiency in %
6 months	Adjusted Imitation Score	.137	-.421*	-.391†	.455*
12 months	Adjusted Imitation Score	.088	-.021	.108	.239

* $p < .05$

† $p < .06$

Note. Correlations in 12-month-olds are controlled for co-sleeping status.

Figures

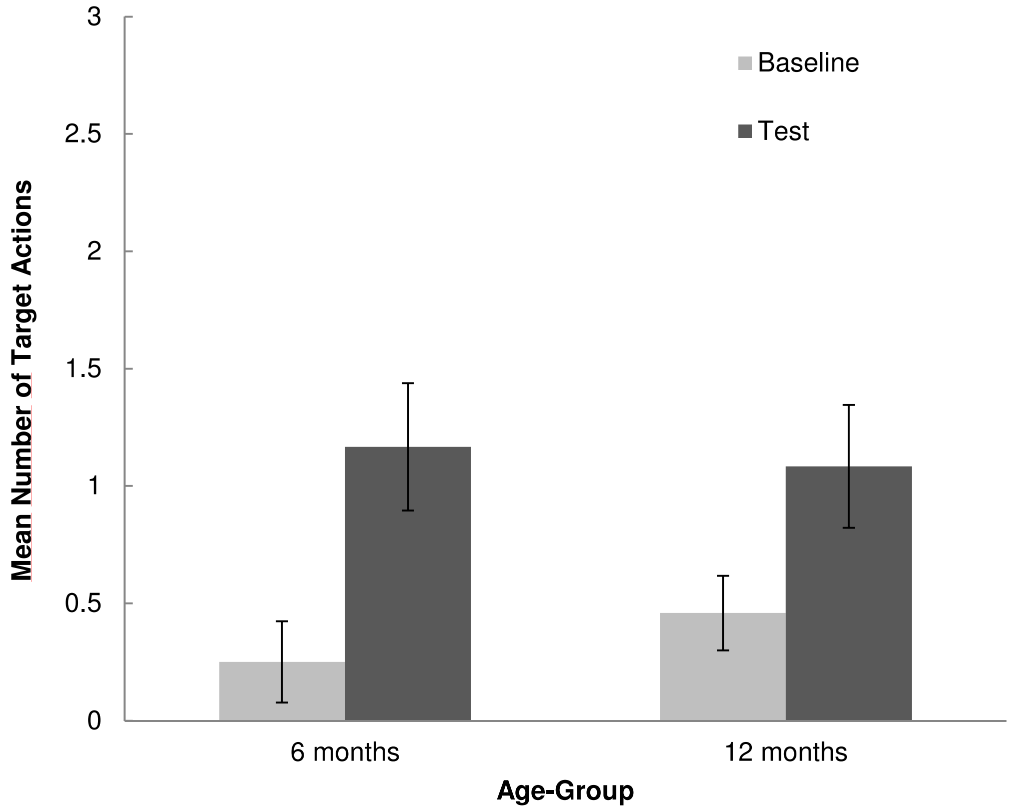

Figure 1.

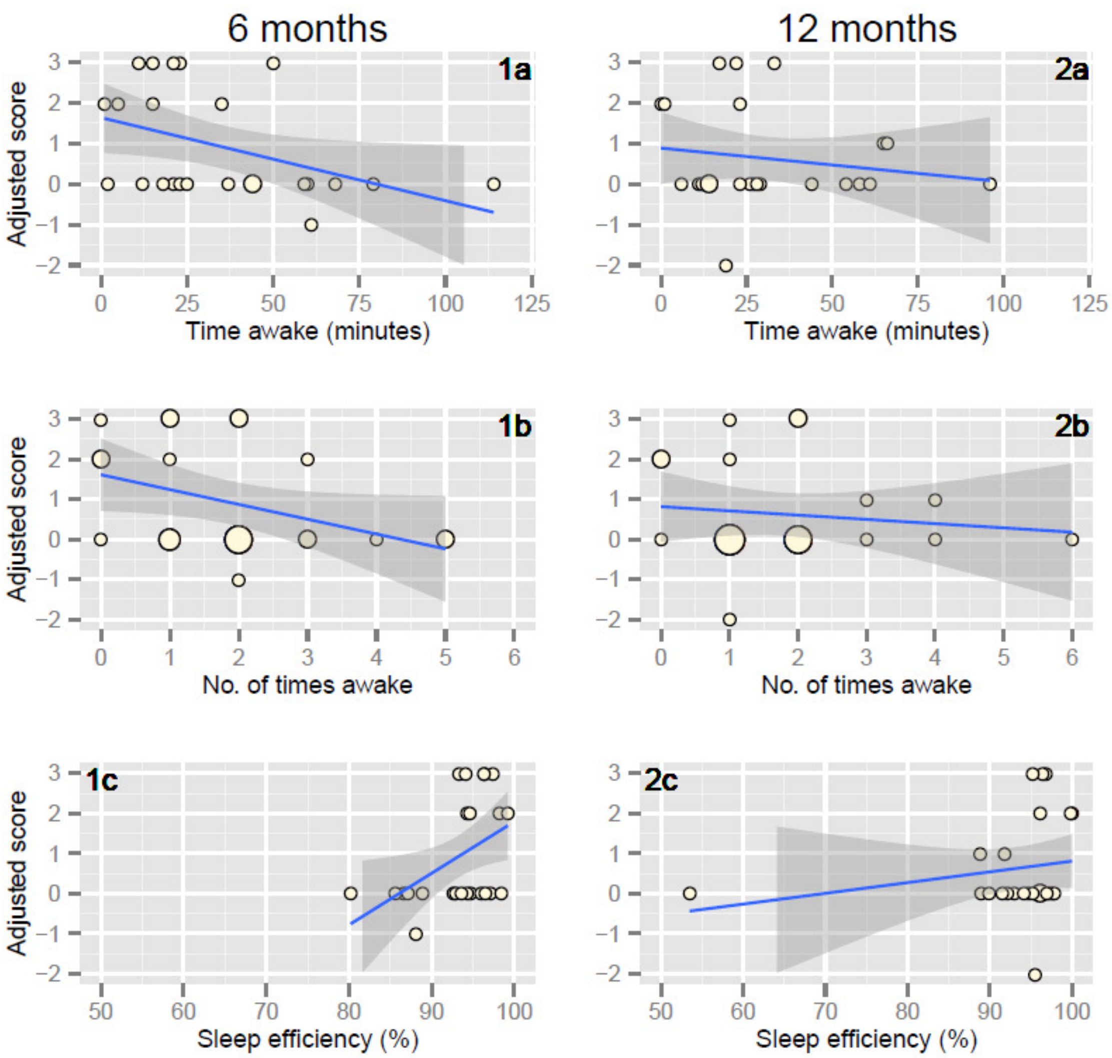

Figure 2.

Note. Column 1 displays the data for 6-month-olds, and column 2 the data for 12-month-olds. Symbol areas are proportional to the number of data at each location. 95% confidence bands about each regression line are also shown.

Captions

Table 1

Means, Standard Deviations and P-Values for Sleep Variables for each Age-Group.

Table 2

Correlations between Night Time Sleep Variables and Adjusted Imitation Score for each Age-Group.

Figure 1. Mean imitation scores as a function of phase and age. Error bars represent *SE* of *M*.

Figure 2. Scatterplots and regression lines of adjusted imitation score against sleep quality variables for each age group.

Running title: Prior sleep is related to infant imitation