Infant wake after sleep onset serves as a marker for different trajectories in cognitive development

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Abstract

Background: Sleep variables have been linked to improved functioning of learning and memory throughout life, with most studies focusing on older children and adults. Since infancy is a time of outstanding plasticity, sleep variables could be particularly important for cognitive development in that age group.

Methods: This is a longitudinal study collecting data from 40 infants at four different time points of 4, 6, 8, and 10 months. Sleep variables were assessed using actigraphy for a week, as well as a sleep questionnaire. Eye-tracking was employed to examine developmental cognitive trajectories. Infants had to remember the location of a toy that had previously been linked to a sound and an eye-tracker recorded whether they were searching the correct location upon hearing the sound.

Results: Based on their trajectories between 4 and 10 months, infants were divided into two groups who shifted their response strategies at different time points. Those two groups also differed in other aspects of their looking patterns and scored increasingly differently in the Ages & Stages Questionnaire over time. Time spent awake in the night early in life was reduced in the group who changed their strategy earlier.

Conclusion: While previous research examined the relation of infant sleep and cognitive functioning measured once, this paper provides first evidence that night wake time can serve as a marker for different cognitive trajectories.

Keywords: Sleep, Working memory, Infancy, Longitudinal studies

Abbreviations:

- NST: Night sleep time
- WASO: Wake after sleep onset
- NWF: Night waking frequency
- DST: Day sleep time

Introduction

Learning and memory are closely connected to sleep throughout life in a bidirectional way (Diekelmann & Born, 2010; Huber & Born, 2014; Walker & Stickgold, 2006). Not only does sleep consolidate previously learned information in infants, children, and adults (Fenn, Nusbaum, & Margoliash, 2003; Friedrich, Wilhelm, Born, & Friederici, 2015; Gómez, Bootzin, & Nadel, 2006; Seehagen, Konrad, Herbert, & Schneider, 2015), high quality sleep also facilitates subsequent learning (Antonenko, Diekelmann, Olsen, Born, & Molle, 2013; Diekelmann, 2014; Feld & Diekelmann, 2015; Van Der Werf et al., 2009). As infancy is a period of particularly high learning demands, regular high quality of sleep is essential to boost learning capabilities (Rasch & Born, 2013). Habitual sleep variables are defined as sleep characteristics, i.e. duration and fragmentation of sleep, which are experienced over several nights by one child at a given age during their development.

Working memory is an important component of learning and executive functioning as it requires maintaining and manipulating information for a short period of time (Baddeley, 2010). A recent meta-analysis which explored the impact of sleep restriction on different aspects of cognition, including 61 studies comprising of mainly teenagers and adults displayed that sleep loss impaired working memory performance (Lowe, Safati, & Hall, 2017). Unlike other aspects of cognition, working memory performance was not moderated by the severity of sleep restriction, suggesting a sensitivity to sleep loss. However, when sleep duration was extended in habitually sleep restricted teenagers, working memory performance improved (Dewald-Kaufmann, Oort, & Meijer, 2013). Although there are few studies investigating the relation between working memory or executive functioning and sleep in children, they do suggest a connection even earlier in development. For example, executive functioning is found to be more advanced in 18-month-old and 4-year old children, who slept proportionally more during the night than during the day (Bernier, Beauchamp, Bouvette-Turcot, Carlson, & Carrier, 2013; Bernier, Carlson, Bordeleau, & Carrier, 2010). The extent to which these findings translate into current infant research still remains unclear.

Infancy is a period of outstanding plasticity, where small alterations in a given factor could also have broad and significant long-term consequences (Karmiloff-Smith, 1998). Therefore, variation in young infants' sleep variables, alongside their impact on learning and memory, could have cascading effects on long-term cognitive trajectories. Research clearly presents that individual variability in habitual sleep is much higher during the first months of life than further on during infancy (Galland, Taylor, Elder, & Herbison, 2012), with some infants requiring more sleep or awakening more often to feed than others. Could these different needs serve as markers for different cognitive trajectories? Cross-sectional studies fail to answer this question in full, as they only take a snapshot without considering potentially non-linear trajectories of habitual sleep as well as memory performance. For instance, Konrad et al. (2016) found that the relation between sleep and imitation memory was inconsistent between age groups, as there were significant cross-sectional correlations at 6 months of age, but not at 12 months of age. However, if individual variations in sleep variables predict different memory trajectories, a potentially longitudinal link might be ignored due to concurrent associations seeming insignificant. Similarly, different sleep variables might be related to memory performance concurrently than those linked longitudinally.

Most studies exploring the link between sleep and cognition in infants measure sleep early on in development and correlated it with mental development later in life, but do not investigate the relation between sleep and cognitive trajectories (Bernier et al., 2010; Gertner et al., 2002), leading to potential non-linear cognitive trajectories being unexplored. For example, one study by Horváth & Plunkett (2016) considered individual trajectories and found that increased naps and higher sleep efficiency predicted earlier vocabulary growth in toddlers assessed at three time points. Since vocabulary growth was not linear but S-shaped, correlations between sleep and the number of known or spoken words at one point in time would have differed for distinct age groups. In addition, the prevalence of this issue increases for cognitive measures where no normative data is available. Therefore, the focus of our study aims to understand what no previous study has recognised: the early markers of infant sleep for trajectories in working memory over the first year of life.

Few longitudinal studies have focused on the relationship between working memory or executive functioning and sleep during development. They suggest that sleep problems in childhood relate directly (Thomas, Monahan, Lukowski, & Cauffman, 2015) or indirectly (Friedman, Corley, Hewitt, & Wright, 2009) to reduced working memory performance in adolescence. Findings of another study presented that 12- and 18-month-old infants with a higher proportion or total sleep occurring at night was related to better executive functioning at 18 and 26 months (Bernier et al., 2010). However, these studies clearly focused on older children and relied on parent-report when assessing sleep; a more detailed and objective method of data collection, such as actigraphy, may be a more appropriate approach. An actigraph is a motion-sensor that is normally attached to the ankle of the infant. Recorded movements help to calculate the periods of time spent in sleep or wakefulness using a predefined algorithm. Although actigraphy is an indirect measure of sleep, it has been validated using polysomnography, direct observation, and videosomnography (Meltzer, Montgomery-Downs, Insana, & Walsh, 2012) and its objective nature is advantageous to parental report, which underestimates time spent awake during the night (Werner, Molinari, Guyer, & Jenni, 2008).

For this research, a paradigm developed by Richardson & Kirkham (2004) was chosen, which relies on eye movements to measure working memory abilities in infants. More specifically, it is a spatial indexing task based on paired associate learning, in which infants become familiarised with two different toys that are paired with a specific sound, each appearing consecutively on different sides of a computer screen. After the familiarisation phase, infants hear each of the two sounds one after another without the appearance of the relevant objects. Looking patterns are recorded to ascertain whether infants remember the visual-auditory pairing and, upon only hearing the sound, look towards the appropriate location where they expect the object to appear. Richardson & Kirkham (2004) used this task when investigating the capacity of adults and 6-month-olds to attach multimodal events to locations, resulting in infants looking more to the side where the toy should have appeared.

In this experiment, sleep variables were assessed longitudinally at 4, 6, 8, and 10 months, using actigraphy and questionnaires for one week prior to testing working . This age range was chosen due to the expectation of interpretable results from the memory task, in addition to this age being a period characterized by a shift of high intra-individual variability to relative stabilisation in sleep variables (Galland et al., 2012; Scher, Epstein, & Tirosh, 2008). Firstly, trajectories in the memory task were explored, hypothesising that performance on the task would improve over time as infants' memory development progressed. Secondly, it was predicted that there were individual differences in working memory performance. Our aim was to group infants depending on their performance trajectories in the working memory task. Finally, it was hypothesised that the group who performed better at an earlier age in the working memory task would wake less during the night and sleep longer.

Methods

Participants and design

Forty healthy 3-month old infants (21 female) were recruited for this longitudinal study from an existing list of parents who volunteered for research at the Procter & Gamble Innovation Centre in Schwalbach, Germany. Infants attended sessions within 2 weeks of 4, 6, 8, and 10 months since their date of birth. All infants were Caucasian, born full-term, with variation in maternal educational background (university degree: n = 9; college: n = 20; schooling complete: n = 11). Fifteen infants were first born and 25 had siblings. Different sleeping arrangements (own room, room-sharing, co-sleeping) were reported by each of the parents and are displayed in Table 1. One infant left the study at 8 months due to illness and one at 10 months as the family had moved away. Additionally, sleep data from two 4-month-olds and one 10-month- old is missing because of equipment failure. Due to poor calibration, eyetracking data from six infants at 4 months, two at 6 months, three at 8 months, and two at 10 months was not collected. Data from the memory task was collected from 33 4-month-old, 38 6-month-old, and 36 8- and 10-month-old infants. All test trials with less than 500ms recorded looking times were excluded. Included trials comprise of 28 for Trial 1 and 23 for Trial 2 at 4 months, 35 for Trial 1 and 37 for Trial 2 at 6 months, 35 for Trial 1 and 2 at 8 months, and 34 for Trial 1 and 35 for Trial 2 at 10 months.

-- Table 1 ---

Procedure

Prior to their visit, families were asked to record sleep data for seven consecutive nights using an actigraph, a sleep diary where they noted bedtimes and wake times, and questionnaires on sleep and general development. Actigraphs were attached to the infant's ankle by the parent, who had received previous training in an introductory session prior to the study. Subsequently, families participated in eye-tracking and interaction tasks including a working memory task in the laboratory. During testing, the infant sat on the caregiver's lap, approximately 50 cm away from the eye-tracker and the screen. The experimenter applied a five-point calibration on the infant's gaze and then started the experimental protocol that included two additional tasks. The working memory task described here was shown after approximately 5 minutes and directly followed a short 'Sesame Street' clip.

Measures and coding

Habitual sleep

Parents were asked to fill in a sleep diary for seven consecutive nights prior to the test session in which they recorded each time their baby fell asleep and awoke. Simultaneously, actigraphy data were recorded for seven consecutive nights using an Actiwatch 2 from Philips, Respironics, which stored movement data every 30 seconds. The times at which the infant went to bed and got up indicated in the sleep diaries were used as boundaries for the start and end time of each night. The Actiwatch data was processed within this time frame using an algorithm from the Respironics Software for this device, which coded each 30-seconds epoch as ’awake’ or ’asleep’ using the dynamic threshold as specified in the software (0:888 * mean activity in the age group). Data was further processed by defining that a sleep interval started when 5 consecutive minutes were coded as asleep and ended when 5 consecutive minutes were coded as ’awake’. Abnormal night (e.g. long car drive) or nights where the actigraph had fallen off, as indicated in the sleep diary, were excluded. Moreover, nights with a duration of two standard deviations below and above the mean were excluded. The mean number of nights recorded per infant and time point was 6.57. Night sleep duration, time spent awake during the night, awakenings, and day sleep duration are commonly used in the infant sleep literature and have been correlated with cognitive performance in previous studies (Konrad, Herbert, Schneider, & Seehagen, 2016; Lukowski & Milojevich, 2013; Scher, 2005). Three different sleep variables were calculated using the definitions from Meltzer, Montgomery-Downs, Insana, & Walsh (2012): Night sleep time (NST), wake after sleep onset (WASO, the time infants spent awake between sleep onset in the evening and sleep offset in the morning), and the average night waking frequency (NWF). For each infant, values were averaged over the whole week. The average day sleep time (DST) and other characteristics of sleep routines such as co-sleeping or solitary sleeping were assessed by the Brief Infant Sleep Questionnaire (Sadeh, 2004).

Memory

During eight familiarisation trials, infants learned to associate the location of one toy that was consistently presented on one side of the screen with a simultaneously presented specific sound, and another toy on the opposite side of the screen with a simultaneously presented different sound. Between trials, an attention grabber was displayed in the centre of the screen, with the next trial only starting after the infant had fixated this point. In each of the two test trials, infants only heard one of the previously presented sounds for eight seconds but did not see any toy in the two frames (Figure 1). All stimuli were taken from Richardson & Kirkham (2004): the visual toys and the auditory stimuli were randomly matched and two fixed pairings were used in the experiment. When infants were 4 months, the first test trial always included the sound of the opposite side as the one presented in the last familiarisation trial. At 6, 8, and 10 months, test trials were presented randomly. To separate the two regions of interest, the screen was divided as in Richardson & Kirkham (2004) and the duration of looking time to the correct and incorrect side was captured. For each infant at each age, the percentage of looking time to the correct side was calculated. Moreover, total looking duration was calculated in addition to the area that infants saw during a given trial. The screen consisted of 1024 x 768 pixels. A 60 x 60 square was drawn around each pixel that the infant had fixated upon, which was then defined as 'seen'. All seen pixels per trial were then calculated.

-- Figure 1 ---

Sleep questionnaire

Parents were asked to complete the Brief Infant Sleep Questionnaire (Sadeh, 2004) to assess day sleep time and co-sleeping. The BISQ was validated using actigraphy and sleep diaries and shows high reliability ($r > .82$, Sadeh, 2004).

Statistical analysis

In this study, we employed multilevel modelling using R and the NLME package (Pinheiro, Bates, DebRoy, Sakar, & Team, 2014) as opposed to repeated measures ANOVAs as it allows for clustering at the infant level as well as at a lower level such as age by regarding repeated measures as 'nested' within individual infants (Field, Miles, & Field, 2012). Moreover, it can handle varying numbers of observations per infant. Several models were first defined, starting with a baseline model without predictors but with Infant as random factor and adding one predictor after another in further models. Those models were then compared with each other to test which predictor significantly ameliorated the model. Details of model parameters are described in the Supporting Information.

Results

Sleep variables

Means and standard deviations of NST, WASO, NWF, and DST for the different time points are presented in Table 2. Repeated measures analyses including one of the sleep variable as the outcome variable and Age in months as the first predictor revealed that gender, siblings, maternal education level, and sleeping arrangement were not related to any of the sleep variables.

Memory

Infant looking times to the correct and incorrect side in the first and second test trial at the four time points are presented in Figure 2. In order to replicate the analyses of Richardson & Kirkham (2004), one repeated measures model was used for each age group with Trial (first vs. second) and Side (correct vs. incorrect) as factors. There were no significant main effects or interactions at 4, 6, and 10 months. At 8 months, there was a marginally significant main effect of Side, $X^2(1) = 3.37$, $p = .067$, and Trial, $X^2(1) = 2.88$, $p = .089$, and a significant interaction between Trial and Side, $X^2(1) = 6.06$, $p = .014$. Infants looked more to the correct and less to the incorrect side in the first test trial ($M_{correct} = 2.52$, $M_{incorrect} = 1.48$) but not in the second test trial ($M_{correct} = 1.52$, $M_{incorrect} = 1.66$). Also, looking times to the correct side in the first test trial at 8 months differed significantly from chance to the time infants spent looking at both sides together, $t(32) = 2.41$, $p = .011$.

-- Figure 2 ---

A repeated measures ANOVA revealed no significant effect of the time infants were tested during the day (morning, midday, afternoon) on the proportion of looking time to the correct side. In addition, gender, number of siblings, and maternal education level did not have an effect on the proportion of looking time to the correct side.

Development of memory over time

Correlation analyses to explore individual stability in the percentage of looking time to the correct side revealed a negative association between 4 and 8 months, $r = -.41$, $p = .03$ (adjusted for multiple tests). More than one trajectory in looking time over different ages was assumed due to infants who looked more to the correct side at 4 months in a given trial (first or second) consequently looked less correctly at 8 months in the same trial, as well as that infants, as a group, not showing a preference for either side at 4 months. In order to explore these multiple trajectories, infants were grouped depending on whether they looked correctly at 4 months; trials with more than 50% of looking time to the correct side were labelled as 'correct' and those with less than 50% of looking time to the correct side were labelled as 'incorrect'. Indeed, t-tests revealed that at 4 months the 'correct' group looked more to the correct side than the 'incorrect' group, $t(48.84) = 10.70$, $p < .001$, whereas the 'incorrect' group looked more to the correct side at 8 months, $t(44.84) = 3.08$, $p = .003$ (see Figure 3a). Moreover, infants' looking times in the two groups were investigated to ascertain whether they differed significantly from chance (50%) at those ages. At 4 months, looking time to the correct side was above chance in the 'correct' group, $t(23) = 7.47$, $p < .001$ (two-sided t-test), and significantly shorter than chance level in the 'incorrect' group, $t(26) = -7.66$, $p < .001$. At 8 months, the 'incorrect' group's looking were above chance levels, $t(23) = 2.68$, $p = .006$. As expected, one sample t-tests were not significant for either group at 6 and 10 months. Those results remained similar when excluding infants with a clear side bias, i.e. infants spending more than 90% of their looking time to the left or right hand side of the screen over both test trials.

One underlying but displaced trajectory was hypothesised in the two groups: when infants initially began to remember the location and the toy they were expecting, they looked more to the correct side. For some infants, this was the case at 4 months, for others only at 8 months. After succeeding in this first step, infants of a more mature age searched the whole screen, potentially because they expected the toy to appear elsewhere when it did not show up in the familiar location. This would suggest that, in the first group, infants who remembered at 4 months would then shift their strategy by searching the whole screen at the later ages, named 'early shifters'. The second group, however, the 'late shifters', only started to remember at around 8 months. The late shifters potentially looked more to the incorrect side at 4 months because test trials were not yet presented randomly, unlike at later assessments, and infants always heard the sound from the opposite side of what they were presented with in the last familiarisation trial. Hence, the late shifters must have continued to attend the side they had just looked at without crossing the midline after attending to the attention grabber.

In order to check the assumption that the early shifters explored a larger area of the screen, a repeated-measures model was conducted, using Area of looking as outcome variable and Group (early shifters, late shifters) as well as Age in months (4, 6, 8, 10) as predictor variables, which displayed a significant main effect for Group, $X^2(5) = 4.17$, $p = .041$. Early shifters searched a larger area of the screen than late shifters, $t(257) = 2.29$, $p = .023$ (see Figure 3b). There was no significant main effect of Group on overall looking duration during a trial, suggesting that the early shifters explored a larger area of the screen than the late shifters in the same amount of time. This finding stayed robust when we removed all babies looking in between 45 and 55 percent to the correct side at 4 months (12% excluded).

-- Figure 3 --

Development of sleep variables over time

Table 2 presents correlations of the sleep variables as well as total scores of the ASQ between ages, adjusted for multiple tests. NST was highly correlated at the later ages whereas WASO and NWF only stayed consistent in younger infants. DST was consistent from one age to the next.

Baseline relation between memory and sleep

In order to explore the relation between memory and sleep at 4 months, repeated measures regression analyses was run. The proportion of looking time to the correct side was entered as outcome variable and Trial (first, second), one Sleep variable (NST, WASO, NWF, DST), as well as the interaction between Trial and the Sleep variable served as predictors. There was a significant main effect for WASO with no significant main effect of trial or significant interaction ($X^2(6) = 7.47$, $p = .006$). Infants who woke less during the night, $t(26) = 2.75$, $p = .010$, and who slept more efficiently, $t(26) = 2.55$, $p = .017$, looked more to the correct side at 4 months in both trials. There was no association between memory and NST, NWF and DST.

Association between memory and sleep variables over time

Multilevel modelling was used to compare sleep variables in the two groups with different cognitive trajectories identified earlier. One sleep variable was included as outcome variable and Age in months (4, 6, 8, 10) as predictor. In a second step, Group (early shifters, late shifters) and in a third step, the interaction between Age in months and Group were entered as predictors. There was a significant interaction between Group and Age in months on WASO, $X^2(6) = 6.96$, $p = .010$ with early shifters being awake for less time, $t(169) = 2.57$, $p = .011$, than late shifters when younger (see Figure 4). Results were robust, when excluding infants who looked between 45 and 55 percent to the correct side at 4 months, $X^2(6) = 5.91$, $p = .015$, $t(169) = 2.43$, $p = .016$.

-- Figure 4 --

Discussion

This study suggests that less habitual wake after sleep onset early in life serves as a marker for better performance in a working memory task over developmental time. Infants in this study were grouped depending on their trajectories in a working memory task and we demonstrated that the two groups were phase shifted, i.e. they showed a similarly shaped response curve that peaked at different points in time. The group with an earlier maturation of memory performance spent less time awake during the night in the first months of life. Night and day sleep time as well as night waking frequency were not related to working memory performance.

Regarding concurrent working memory performance, we failed to replicate the results of Richardson & Kirkham (2004) as 6-month-olds as a group looked longer to the correct side in Richardson and Kirkham's study unlike in this report. Richardson & Kirkham tested in total

11 infants who repeated the entire task up to 5 times per assessment. Potentially, more infants were selected in their study who looked longer to the correct side at a younger age. Also, the multiple repetitions of the whole task could have led to a training effect which encouraged infants to search more at the correct location after a first repetition. Moreover, it is possible that infants who looked predominantly to the correct side also attended more task repetitions in the Richardson & Kirkham study, which would have led to a more positive group outcome. Finally, infants were only tested at one age, taking just a snapshot instead of providing information on how individuals performed over developmental time in the same task.

This study displays an underlying but phase shifted trajectory in the working memory task that can be described in the following way: As infants' memory abilities are initially limited (Reynolds & Romano, 2016) it is likely that infants could not remember the toy during the first months of their life. At an intermediate age, infants remembered correctly and consequently searched more at the side where they expected the toy to appear. However, at a mature age, they realised quickly that the toy did not come up and, therefore, scanned the whole screen. Other studies on distinct memory processes support the finding that memory abilities change and improve during the first year of life (Reynolds & Romano, 2016; Reznick, Morrow, Goldman, & Snyder, 2004). Also, infants have difficulties binding object location and features for identification early in life (Kaldy & Leslie, 2003; Mareschal & Johnson, 2003; Newcombe, Huttenlocher, & Learmonth, 1999) and only succeed when older (Kaldy & Leslie, 2005). One aspect that those cross-sectional studies lack, is that they cannot identify groups of infants with different trajectories, as we did here: the early shifters reached the mature level of ability by 6 months whereas the late shifters reached it by 10 months. A natural follow-up question – which is, however, beyond the scope of this paper – is how these groups perform on other dimensions. In the supporting material, we show that the Early shifters exhibit better overall development over time as measured by the Ages & Stages Questionnaire Third Edition (Squires, Twombly, & Diane Bricker, 2009).

To our knowledge this is the first study displaying that habitual night wake duration serves as a marker for trajectories in a working memory task in infants: Early shifters spent less time awake during the night than late shifters in the first few months of life. The difference in twake after sleep onset between the two groups was greatest at 4 months, suggesting that especially sleep variables early in life are related to working memory trajectories. The group difference in WASO (mean: 8.36min; median: 10.88min) is meaningful considering that this made up to a quarter of time spent awake in the late shifter group. Also, WASO in the early shifters at 4 months was only comparable to WASO in the late shifters when they were two months older. As WASOwas stable at the younger ages, it was not just coincidentally affected by factors such as teething that could have disturbed performance in the task momentarily.

In the current study, time spent awake in the night, but not night and day sleep duration, turned out to be the variable most strongly related to working memory performance. This finding is supported by other correlational studies that associated sleep variables assessed via actigraphy with aspects of concurrent cognitive development in infants (Konrad, Herbert, Schneider, & Seehagen, 2016; Scher, 2005) It is only in studies on teenagers and adults that a change in sleep duration, i.e. sleep restriction or extension, was associated with a change in working memory performance (Dewald-Kaufmann et al., 2013; Lowe et al., 2017). Sleep duration might be a factor that increases in importance later in life as infants in our study were not sleep deprived and it is likely that each individual probably slept depending on his or her needs for optimal functioning during the day. Moreover, only the time spent awake during the night, but not the number of awakenings were associated with working memory development, suggesting that infants who settled back to sleep more easily after waking in the night are more likely to perform better in the working memory task. Night waking is normal during the first months of life and often more prevalent in breast-fed infants, which is most likely not an indicator for sleep problems in generally typically developing infants (Hysing et al., 2014). Difficulties with settling back to sleep and thus increased WASO could, however, be a marker for poorer sleep quality. This would be consistent with other longitudinal studies which found a link between sleep problems in childhood and decreased performance in executive functioning in teenagers (Friedman et al., 2009; Thomas et al., 2015). Given that parents often underestimate infant sleep fragmentation (Werner et al., 2008), our findings emphasise the importance of objective measures such as actigraphy when investigating the link between sleep and cognition.

There are three ways in which the role of habitual sleep for learning and development might be considered. First, Van Der Werf et al. (2009) as well as Antonenko, Diekelmann, Olsen, Born, & Molle (2013) suggest that quality sleep enhances the general subsequent ability of the brain to store and memorise events at one point in time. This research may therefore support the idea that the brains of infants experiencing less time spent awake in the preceding nights were therefore potentially better prepared to process information the following day. This displays advantageous short-term effect on learning, with a potential for long-term consequences, which would explain why early sleep after wake onset was also a long-term indicator for working memory development in this study. Second, habitual sleep has an effect on performance during the day by increasing attentiveness and focus (Weissbluth & Liu, 1983), which could have led to a better performance in the working memory task. Third, sleep and cognition could both be mediated by other factors such as the maturational status of the infant. Some studies have tried to assess the maturation of infants and indicate that sleep might serve as a developmental indicator of risk as, for example, shown in a study on newborn babies by Minard, Freudigman, & Thoman (1999) where sleep cyclicity in newborns and 6-month-olds was related to birth weight and subsequent mental development.

One limitation of this study is that it relies on one single task to assess working memory. Even though the validity of the grouping with respect to different trajectories in the working memory task was confirmed by looking patterns, future studies using other working memory tasks are needed to confirm our results. Furthermore, because the infants in this study were between 4 and 10 months old, we think that the validity of our results is limited to that age range. Finally, we did not collect data on breast-feeding, which has been associated with sleep variables as well as cognitive development in previous studies and thus could be a confounding factor that we did not control for.

This study highlights the importance of longitudinal studies in order to trace developmental trajectories and truly understand associations between different determinants of development. The panel nature of our data was crucial to find two groups of infants with different working memory trajectories and to compare their sleep variables early in life. A snapshot of just the 8-month-old infants of this study, for example, would have suggested that more wake after sleep onset is related with better working memory performance. Furthermore, if mostly early or late shifters had been randomly selected, no correlation would have been found.

Conclusion

In summary, this study suggests that less time spent awake during the night early in life can be a marker for better performance in a working memory task over developmental time. Future studies are warranted to disentangle whether different aspects of cognition, such as executive functioning, language development, and memory, are differently related to sleep variables. Also, more long-term studies are needed to investigate the predictive power of assessments such as the working memory task.

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Figures and Tables

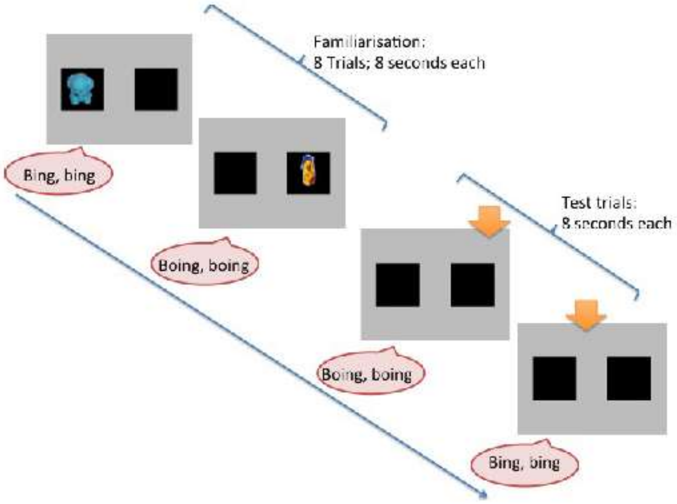

Figure 1: Illustration of the memory task.

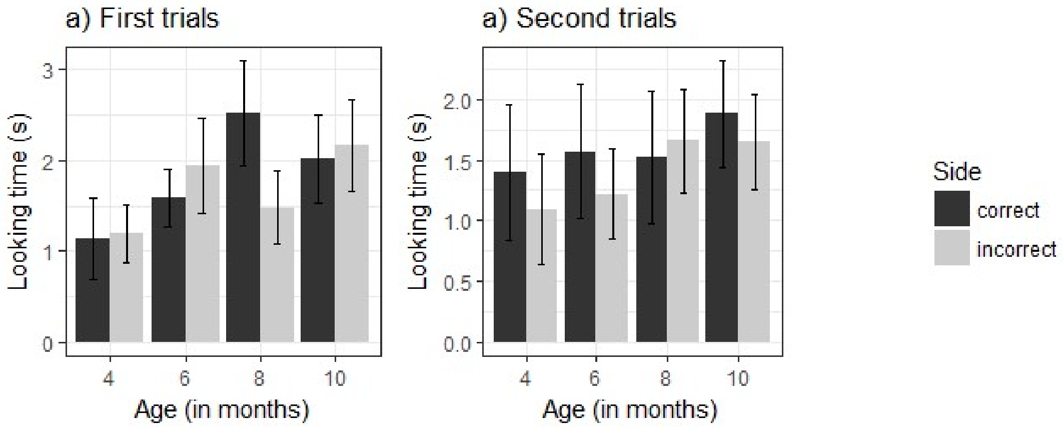

Figure 2: Looking time to the correct and incorrect side in the memory task at 4, 6, 8, and 10 months with 95% errorbar.

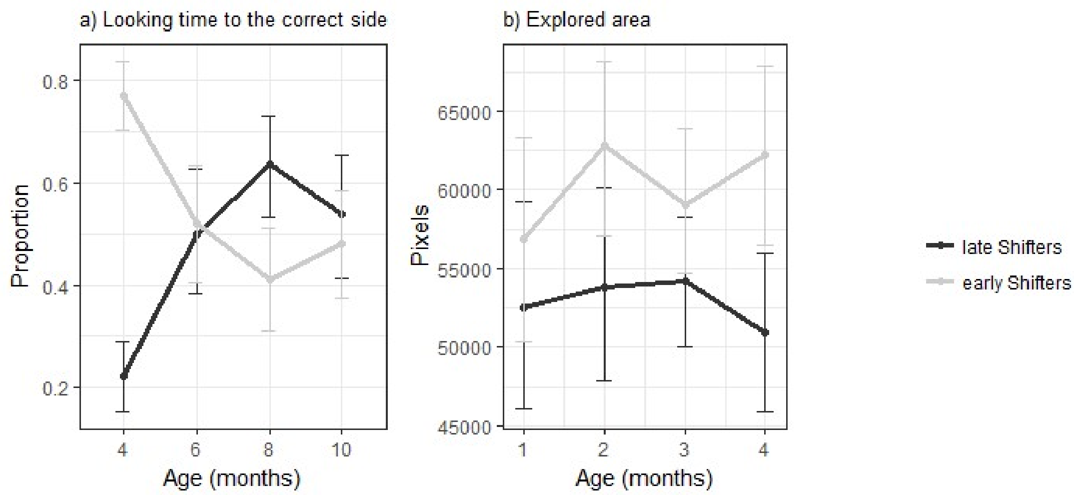

Figure 3: Looking patterns in the memory tasks in early and late shifters.

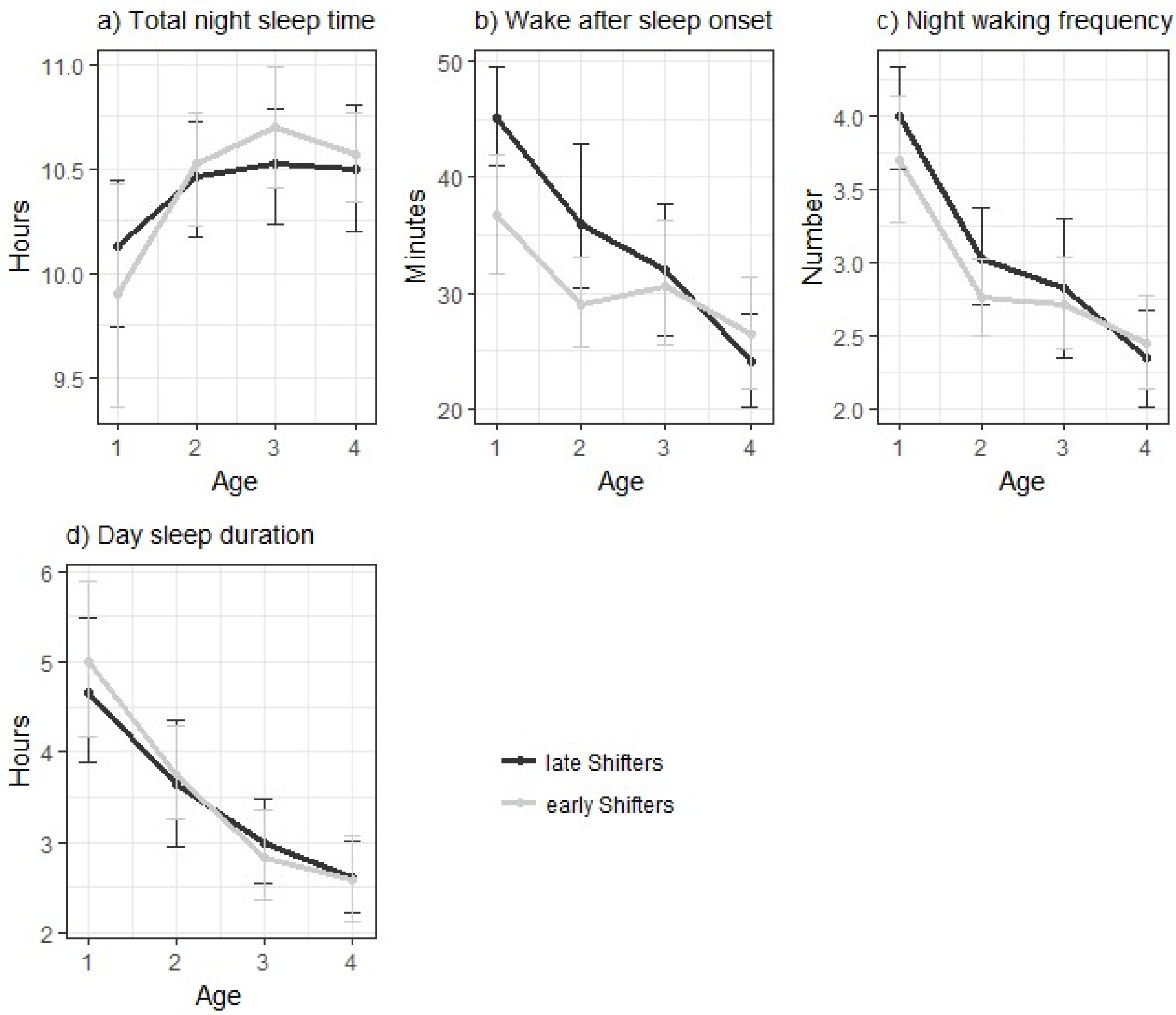

Figure 4: Sleep variables with 95% CI error bar of early shifters and late shifters.

Table 1: Number of infants in different sleeping arrangements at 4, 6, 8, and 10 months

Age (months)	Own room	Room-sharing	Co-sleeping
4	5 (13%)	26 (68%)	7 (18%)
6	7 (18%)	25 (64%)	7 (18%)
8	12 (30%)	19 (48%)	9 (22%)
10	14 (37%)	18 (47%)	6 (16%)

Table 2: Mean, standard deviation, and correlation (adjusted for multiple tests) for each sleep variable.

Variable	Age	M	SD	Correlation		
				6 months	8 months	10 months
NST (hours)[a]	4	10.02	1.11	0.35	0.25	0.34
	6	10.50	0.77		0.59 **	0.55 **
	8	10.66	0.74			0.63 **
	10	10.53	0.82			
WASO (min)[a]	4	39.84	15.13	0.41*	0.32	0.22
	6	31.91	15.43		0.17	0.26
	8	30.42	15.21			0.24
	10	25.06	11.97			
NWF (freq)[a]	4	3.74	1.15	0.53**	0.4	0.17
	6	2.81	1.00		0.38	0.37
	8	2.53	1.07			0.28
	10	2.27	0.85			
DST (hours)[b]	4	4.64	2.12	0.82**	0.34	0.13
	6	3.52	1.51		0.52 **	0.39
	8	2.90	1.25			0.90 **
	10	2.66	1.13			

* for $p < .05$; ** for $p < .01$; NST: night sleep time; WASO: wake after sleep onset; NWF: night waking frequency; DST: day sleep time; [a]: measured using actigraphy; [b]: measured using a questionnaire

- Sleep is essential for learning and memory across the lifespan.
- This paper investigates whether the particularly high inter-individual differences in infant sleep duration and fragmentation are indicative for cognitive trajectories over a prolonged period of time.
- We used eye-tracking to examine developmental trajectories in a task that assesses working memory, an important component of cognitive development, and actigraphy to assess infant sleep variables.
- Based on their trajectories between 4 and 10 months, infants were divided into two groups who shifted their response strategies at different points in time.
- Those who experienced less time spent awake in the night belonged to the group who demonstrated a more mature strategy earlier in life.