THE ROLE OF SLEEP IN EARLY LANGUAGE ACQUISITION

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ABSTRACT

The relationship between sleep and language during infancy has not attracted a great deal of scrutiny despite its theoretical importance in the function of sleep and the practical implications to which resulting findings could contribute. With this in mind, the current thesis aims to investigate this question with a focus on word learning, generalisation of word meanings and vocabulary development. An experimental design in 16 month old infants was used as one of the main approaches to test the potential effects of naps on word learning and generalisation. In both experiments, infants were randomly assigned to nap or wake conditions. After teaching two novel object-pairs to them, their initial performance was tested with an intermodal preferential looking task. An increase in target preference indicated the recognition of the auditory label—looking behaviour being monitored with an automatic eye-tracker. In the case of word learning, the same objects were shown in the test trials as in the training trials, whereas the test objects were different in colour in the generalisation experiment. In both experiments target preference increased only after a nap, while there was no change in the performance of the wake groups. These results indicate that daytime napping facilitates both the consolidation of novel words and the generalisation of novel word meanings in infancy. The relationship between sleep and vocabulary development was studied in a longitudinal questionnaire based design, in which vocabulary questionnaires and sleep diaries were employed, with a cohort of 246 children between the ages of 7 and 38 months being analysed. Sleep measures were used as predictors in a multi-level growth curve analysis of vocabulary development. The length of daytime naps was positively correlated with both expressive and receptive vocabulary growth, whereas the length of night-time sleep was negatively associated with rate of expressive vocabulary growth. To conclude, the results of the present thesis highlight the importance of daytime naps in early childhood.

CHAPTER 1. GENERAL INTRODUCTION AND OVERVIEW

Humans spend one third of their lives asleep, yet research is still not able to provide a definite answer as to why. In order to gain an answer to this question, the present thesis takes as its focus one particularly special group of humans whose time spent in the state of sleep is even longer: infants—suggesting that sleep may be even more crucial for them. Given that a large number of studies on adults have concluded that there is a relationship between sleep and memory (for an extensive review, see Rasch & Born, 2013), there is every reason to hypothesise that sleep plays an important role in infants' cognitive development. Regarding both adults and children, a number of studies have looked at the question of how language specific processes benefit from sleep (e.g. Dumay & Gaskell, 2007; Henderson, Weighall, Brown & Gaskell, 2012). However, we do not know whether a similar relationship exists in infants who are undergoing the most intensive period of acquiring their mother tongue. Thus, the aim of this thesis is to investigate the impact of sleep in early language acquisition, concentrating on word learning and vocabulary development. In addition to broadening our theoretical knowledge, with regard to both sleep and language development, the research outlined in the current study may have important practical implications for parenting and sleep related educational policies.

The aim of this chapter is to provide a solid general overview of the specific research domain. We begin by summarising the research literature that has dealt with the relationship between sleep and cognition in adults, children and infants, and the most influential theories providing a cogent explanation for such a connection. After which we turn to the question of how language related processes are linked to sleep in adults, children and infants. Having done so, we are then able to tackle the literature on early language development, concentrating on word learning, generalisation of word meanings and vocabulary development. Finally, we provide a summary of how sleep develops over the first three years of life.

Sleep and cognition

The definition of sleep

Sleep is a complex physiological phenomenon with specific behavioural and neural characteristics. The characteristics accompanying sleep in humans include: minimal body movement, closed eyes, horizontal lying body position, together with reduced responses to external stimulation (Rasch & Born, 2013). Sleep is also accompanied by a loss of consciousness, which is, importantly, rapidly reversible (Peigneux, Urbain & Schmitz, 2012).

More specifically, sleep is a special state of the brain with altered neural functioning, characterised by electrophysiological changes that are not homogeneous—in that they not only show ontogenetic development, but they also vary throughout the night. Adult sleep consists of two distinct core stages: non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep. The former stage can be further divided into three or four sub-stages according to the depth of sleep, as indicated by the predominance of slow wave activity (SWA). Stage 1 of NREM is an intermediate state between sleep and wakefulness. Almost fifty percent of adult sleep takes place in stage 2, during which characteristic waveforms of waxing and waning sleep spindles—accompanied by low frequency, high amplitude K complexes—occur. Instead of drawing the distinction between stage 3 and 4 according to the classic criteria set out by Rechtschaffen and Kales (1968), researchers determine slow wave sleep (SWS) as the deepest sleep stage during which low frequency, high amplitude electroencephalographic (EEG) oscillations are prevalent. During REM sleep, wakeful like EEG activity of low amplitude and high frequency is apparent, in addition to rapid eye movement and muscle atonia, alongside phasic muscle contractions. NREM and REM sleep follow each other in cycles of approximately 90 minute duration under ultradian regulation. Whilst at the beginning of the night, NREM is more predominant, towards the morning REM sleep becomes more prevalent (Peigneux et al., 2012; Rasch & Born, 2013).

As regards to the timing of sleep, this is precisely regulated by two processes: the homeostatic and the circadian process (Borbely, 1982). With time spent awake, the need for sleep accumulates; hence, sleep pressure increases. Whilst sleep pressure decreases gradually during the following period of sleep. Circadian regulation—an endogenous 24 hour rhythm of sleep propensity and alertness—works against homeostatic sleep pressure during day, though with it during the night. As a result, sleep normally occurs during night (Borbely, 1982; Peigneux et al., 2012).

The function of sleep

The complex function of sleep is far from being understood. If we consider the fact that almost all animals sleep, despite being vulnerable and in danger during this state, there is good reason to support the claim that sleep is essential (Rasch & Born, 2013). Some of the general biological functions with which sleep has been compared include energy-saving (Berger & Phillips, 1995), restoration of energy and cell repair (Oswald, 1980), thermo (Rechtschaffen & Bergmann, 1995) and metabolic regulation (Knutson, Spiegel, Penev & Van Cauter, 2007) and immune functions (Lange, Dimitrov & Born, 2010). As Rasch and Born (2013) suggest, for these functions the loss of consciousness and responsiveness is not required. On the basis of the altered neural functions, it is more likely that it is the brain that mainly benefits from sleep. Moreover, there are many different neurophysiological processes which have been proposed, such as the detoxification of the brain (Inoue, Honda & Komoda, 1995) or glycogen replacement (Scharf, Naidoo, Zimmerman & Pack, 2008). However, the most widely accepted view is that sleep plays a role in memory functions and synaptic plasticity (Diekelmann & Born, 2010; Rasch & Born, 2013; Tononi & Cirelli, 2006, 2014).

Neurocognitive processes related to sleep in adults

Numerous studies have found an association between neurocognitive processes and sleep. In the brief overview given below four main areas are concentrated on: encoding, consolidation, integration and association, and emotional processing (Diekelmann & Born, 2010; Rasch & Born, 2013; Stickgold & Walker, 2013; Walker, 2012; Walker & Stickgold, 2010).

Studies investigating the relationship between sleep and encoding mainly compare learning ability differences between a sleep deprived and a control group. In one study, Harrison and Horne (2000) found that memory retention for the time when an event occurred was significantly impaired in the sleep deprived group. Furthermore, in a functional magnetic resonance imaging (fMRI) study, the temporal lobes were less active during verbal learning in the sleep deprived group. However, the prefrontal and the parietal cortices showed increased activation (Drummond et al., 2000). Moreover, sleep deprivation seemed to especially affect emotionally positive memories (Walker, 2012). These results suggest that sleep has an important role in preparing the brain for learning (Walker, 2012).

There have been numerous studies showing that sleep helps to consolidate different types of memories (Diekelmann & Born, 2010; Rasch & Born, 2013; Walker, 2012; Walker & Stickgold, 2006), as the earliest reports from the beginning of the nineteenth century (Jenkins & Dallenbach, 1924). Gais and colleagues (Gais, Molle, Helms & Born, 2002) not only found a sleep dependent gain on word-pair association tasks, but also showed that the improvement correlated with sleep spindle density. Furthermore, sleep protected declarative memories from interference (Ellenbogen, Hulbert, Stickgold, Dinges & Thompson-Schill, 2006). SWA were also shown to be important in the consolidation of declarative memories (Gais & Born, 2004). Moreover, Marshall and colleagues (Marshall, Helgadottir, Molle & Born, 2006) induced slow oscillations by direct current stimulation during SWS, which resulted in an enhanced retention of the learned stimuli. This implies that a causal relationship exists between SWS and memory consolidation.

In addition to declarative memory, procedural memory also benefits from sleep (Walker & Stickgold, 2006). In a sequential finger tapping task, an improvement can be observed both in speed and accuracy after sleeping (Walker, Brakefield, Morgan, Hobson & Stickgold, 2002). It has also been suggested that during sleep smaller motor memory units are become united into one memory element (Walker & Stickgold, 2006). However, Robertson, Pascual-Leone and Press (2004) found only a sleep-dependent improvement when subjects explicitly learned a sequence of finger movements as opposed to implicit learning. NREM sleep stage 2 has mainly been associated with the sleep dependent gain in procedural memory (Walker & Stickgold, 2006), although correlations with REM sleep have also been observed (Fischer, Hallschmid, Elsner & Born, 2002). SWA seems to play an important role, as suggested by Huber and colleagues' findings (Huber, Ghilardi, Massimini & Tononi, 2004). After a motor reaching-adaptation task, an increase in SWA over the parietal cortex was present whilst sleeping and correlated with the sleep-dependent improvement (Huber et al., 2004). In addition, if a subject's hand was immobilised, reduced SWA was observed in the corresponding brain areas during the subsequent sleeping period (Huber et al., 2006).

Although the majority of the published studies reported sleep-dependent improvement in memory consolidation, contradictory results have also been found (Rasch & Born, 2013). It is clear that experimental design has an effect on outcome. Generally, as mentioned before, sleep-dependent memory consolidation is more robust under explicit learning conditions (Fischer et al., 2002; Fischer, Wilhelm & Born, 2007; Korman et al., 2007; Rasch & Born, 2013; Robertson et al., 2004). Furthermore, the initial strength of encoding has been proposed to affect how memories are consolidated during sleep (Stickgold, 2009); however, results are inconsistent (Rasch & Born, 2013). Moreover, if memories are relevant to the future plans of the individual, sleep-dependent strengthening is greater (Rasch & Born, 2013). Finally, emotions may alter the way in which memories are consolidated (Rasch & Born, 2013; Walker, 2012).

But sleep does not just simply strengthen memory traces, it facilitates the reorganisation of memory and it can lead to the generation of new schemas. Chatburn, Lushington and Kohler (2014) reviewed seventeen studies on the role of sleep in rule extrapolation and found a moderate effect of sleep in their meta-analysis. These studies used a variety of experimental designs, from number reduction tasks with a hidden shortcut (e.g. Wagner, Gais, Haider, Verleger & Born, 2004), through visual transitive interference tasks measuring participants' ability to find the relationship between unlearned pairings of stimuli (e.g. Ellenbogen, Hu, Payne, Titone & Walker, 2007), to several probabilistic learning tasks (e.g. Fenn, Nusbaum & Margoliash, 2003). They also reviewed studies on item integration and found a moderate to large effect for sleep. As all the reported five studies were language related, we discuss these in the next section. Sleep also facilitates multi-item generalisation and gist extraction, as was found in four studies that used false memory recognition (Darsaud et al., 2011; Fenn, Gallo, Margoliash, Roediger & Nusbaum, 2009) or recall paradigms (Diekelmann, Born & Wagner, 2010; Payne et al., 2009). Walker (2012) proposes that while sleep may initially strengthen memories of individual items (episodic memory), later on—before these individual memories start to fade—sleep assists the process of extraction and generalisation for key information into a more adaptive semantic network.

Research on sleep and emotional regulation is more limited. What is known is that sleep seems to influence both affective reactivity and emotional information processing in that sleep loss causes an increase in emotional disturbance assessed through mood questionnaires (Dinges et al., 1997), in addition to amplifying negative emotional reactivity to upsetting daytime events (Zohar, Tzischinsky, Epstein & Lavie, 2005). Increased activity of the amygdala have been reported in sleep deprivation (Yoo, Gujar, Hu, Jolesz & Walker, 2007) in addition to a reduced functional connectivity between the medial prefrontal cortex and the amygdala (Sotres-Bayon, Bush & LeDoux, 2004), indicating that the top-down inhibitory function of the prefrontal cortex has not been restored during sleep (Walker, 2012).

It is well-known (Sharot & Phelps, 2004) that there is an interplay between encoding of memories and the evoked emotions, but emotions may also alter how memories are consolidated, the process of which may be sleep dependent. For instance, Hu, Stylos-Allan and Walker (2006) found that the consolidation of emotionally arousing pictures is superior only after sleep; a finding which was replicated using texts as stimuli (Wagner, Gais & Born, 2001). REM sleep has been proposed to be important in sleep dependent emotional processes during which elevated cholinerg and theta oscillatory activity may provide a favourable environment for selectively enhancing affective memories (Wagner et al., 2001; Walker, 2009, 2012).

The Sleep-dependent Memory Triage model proposed by Stickgold and Walker (2013) attempts to incorporate the above findings in one model. After encoding, during the 'triage' (i.e. selection of memories to consolidate), salience tags are attached to memories on the basis of prior wake experience. In this way, memories that are to be retained become selected and go through consolidation strengthening and enhancing these memories. However, 'memory evolution' can also occur indicated by qualitative changes in memories, and also suggesting that new memories can evolve. What is not clear is whether the consolidation and memory evolution processing happens in parallel or in series. Similarly, further research is needed to clarify the underlying neurophysiological mechanisms.

Neurocognitive processes related to sleep in children and infants

Studies carried out in children show similar, although somewhat stronger, sleep-dependent memory consolidation of declarative and emotional memories in adults. However, procedural memories do not seem to benefit from sleep (Wilhelm, Prehn-Kristensen & Born, 2012). Backhaus and colleagues (Backhaus, Hoeckesfeld, Born, Hohagen & Junghanns, 2008) taught 40 word-pairs to 9-12 year olds and tested them 12 and 24 hours later using a cued recall task. After sleep, there was a marked improvement in performance correlated with the time spent in NREM sleep. Wilhelm, Diekelmann and Born (2008) have confirmed these results using an object-location task. Interestingly, while the amount of SWS was about twice as much in children than in adults, the sleep-dependent gain in memory performance was similar. This implies that children needed a larger amount of SWS for the same sleep-dependent gain.

Additionally, a beneficial impact of midday naps on declarative memories was found in pre-schoolers. Kurdziel, Duclos and Spencer (2013) trained 3-5 year old children during the morning on a visuospatial task in which the children had to remember the location of pictures. Recall was tested immediately after, with no initial difference found between the nap and the wake conditions. A second test was conducted in the afternoon, after the nap group had had an afternoon nap (the wake group was awake throughout this period). The findings clearly indicated that the performance of the nap group was significantly better than that of the wake group, the wake group's performance having declined. Children were also tested in the morning of the following day, and both groups' performance remained around the same level as in the second testing; meaning that the nap group's improved recall was long-lasting and the night time sleep had not restored the performance of the wake group. Furthermore, sleep spindle density correlated positively with the performance improvement following the nap echoing findings in adults (Gais et al., 2002). These research outcomes were also separately examined in habitually napping (children who napped more than five days per week) and non-habitually napping children. Interestingly, only habitually napping children benefited from daytime rest. Kurdziel and colleagues argue that in those children who do not nap habitually memories are more stable and less likely to decay. It is possible that in a less mature brain (i.e. in habitual nappers) more frequent consolidation is necessary due to the smaller capacity of hippocampal stores and/or less efficient consolidation during wakefulness (Kurdziel et al., 2013).

Similar results have been shown in 6 and 12 month old infants. Seehagen, Konrad, Herbert and Schneider (2015) used a deferred imitation task in which three target actions were carried out on a puppet in order to assess declarative memory consolidation. Following the learning session, infants were tested after delays of 4 and 24 hours in two separate experiments. One group had a nap with the 4 hour retention period, while the other group remained awake. In addition, there was a baseline condition in which infants did not see the demonstrations of the target actions. In both experiments, only those infants who had napped within 4 hours of the demonstration were able to remember and successfully produced the target actions. There was no significant effect for age, indicating that 6 and 12 month olds benefit equally from napping. These results further support the finding that in infancy frequent naps are necessary in order to be able to efficiently consolidate memories.

Regarding emotional memories, studies compared the impact of sleep in consolidating emotional and neutral stimuli using pictures (Prehn-Kristensen et al., 2009; Prehn-Kristensen et al., 2013). Similar to the result found in adults, consolidation of pictures that evoke negative emotions benefited more from nocturnal sleep. Furthermore, the difference in the sleep-dependent improvement between the two (neutral and negative) picture types was greater in children (Prehn-Kristensen et al., 2013), suggesting that emotions may play a more important role in selecting which information should be consolidated.

However, findings are less clear regarding procedural memory consolidation. In a serial reaction time task, in which participants had to repeatedly press buttons in a sequence as fast as possible, sleep impaired motor sequence learning. In this reaction time task, the buttons to be pressed were cued, with the sequence following an underlying rule—a rule which the participants were not aware of. Despite this, the participants implicitly learnt the sequence as reflected by reduced reaction times compared to reaction times in randomly cued sequences. After a period of wake, performance did not changed. However, performance did deteriorate following sleep in children in contrast with adults whose performance improved following sleep (Fischer et al., 2007). This finding is further supported by Wilhelm et al. (2008), who reported improved performance on a finger tapping task after wake compared to sleep; and by Prehn-Kristensen et al. (2009), who showed similar results in a mirror tracing task in which participants were asked to draw by watching their hands in a mirror. Wilhelm, Prehn-Kristensen, et al. (2012) claim that it is not necessarily that sleep-dependent consolidation of procedural memories is different in children, but that these processes may be more efficient in encoding such memories during wake. This is supported by a study looking at differences between 9 year olds and 17 year olds which compared the stability of learning on a finger sequence tapping task after wakefulness. The adolescents were more prone to interference after being given an additional sequence to learn (Dorfberger, Adi-Japha & Karni, 2007). On the other hand, the different level of pre-sleep performance may be behind the lack of sleep-dependent consolidation of procedural memories, especially considering the fact that children have worse motor performance (Wilhelm, Prehn-Kristensen, et al., 2012). Wilhelm and colleagues (Wilhelm, Metzkow-Meszaros, Knapp & Born, 2012) manipulated training on a motor sequence in adults and children in order to create different pre-sleep levels of performance. A group of children received extensive training, whereas the training was restricted for a group of adults, both cohorts producing intermediate level performances. It was in these two groups only that sleep facilitated the consolidation of the motor sequence, suggesting that pre-sleep performance is an influential factor.

In a more recent study, however, a clear difference was shown in sleep-dependent memory consolidation in children compared to that of adults (Wilhelm et al., 2013). After an implicit motor learning task involving pressing cued buttons, participants were not only tested implicitly (on how fast they could press the buttons), but they had to explicitly recall the sequence. After sleep, both adults and 8-11 year old children became better at explicit recall, although children benefited more. Moreover, this greater explicit knowledge was associated with the higher SWA during sleep and stronger hippocampal activation during recall. This suggests that sleep in children promotes the extraction of rules and invariant patterns more than in adults.

Theories explaining the sleep-cognition association

There are two widely accepted theories attempting to describe the fundamental neurophysiological mechanisms of the findings detailed above showing an enhancing role of sleep in cognitive processes: the Active System Consolidation Hypothesis (ASC) and the Synaptic Homeostasis Hypothesis (SHY).

The ASC builds on the widely accepted standard two-stage memory system (Born, Rasch & Gais, 2006; Marr, 1971) according to which firstly, memories are rapidly encoded into short-term stores (in the hippocampus) from where they are gradually transferred at the second stage to the slower learning long-term stores. We give an overview of the model on the basis of the reviews of Diekelmann and Born (2010) and Rasch and Born (2013). The ASC proposes that repeated reactivation of memories during sleep enable such a transfer to become possible; moreover, for this, the precisely coordinated oscillatory activity of sharp wave-ripples (oscillatory patterns in the hippocampus), sleep spindles and SWA is necessary. It has been shown that during sleep those hippocampal neurons become active which are the ones that were firing during learning whilst awake, with sharp wave-ripples accompanying this reactivation in the hippocampus (Clemens, Fabo & Halasz, 2006; Nadasdy, Hirase, Czurko, Csicsvari & Buzsaki, 1999; Wilson & McNaughton, 1994). Moreover, they correlated with the consolidation of visual stimuli in epileptic patients in whom intracranial electrodes allowed researchers to record EEG activity from the peri- and entorhinal cortices (Axmacher, Elger &

Fell, 2008). The causal role in sleep-dependent memory consolidation was also suggested by demonstrating that the selective disruption of sharp wave-ripples in rats impaired the formation of long-term memories (Girardeau, Benchenane, Wiener, Buzsaki & Zugaro, 2009). Sleep spindles and sharp wave-ripples are temporally coupled, with ripples appearing in the troughs of the spindle activity (Clemens et al., 2007; Sirota, Csicsvari, Buhl & Buzsaki, 2003). Sleep spindles are thought to play a role in synaptic plasticity. Many studies found a correlation with spindle activity and memory consolidation in humans (Diekelmann & Born, 2010). Furthermore, spindles occurred in brain regions which were active during encoding (Clemens, Fabo & Halasz, 2005; Clemens et al., 2006; Schmidt et al., 2006). In addition, they may have a role in triggering long-term potentiation (LTP, Rosanova & Ulrich, 2005) and synchronising those neurons which were potentiated during encoding (Werk, Harbour & Chapman, 2005). SWA seems to synchronise the spindle and ripple activity as both appears in the up-states of the slow oscillation (Molle, Marshall, Gais & Born, 2002; Sirota et al., 2003; Steriade, 2006), with this supporting the dialogue between the hippocampus and the neocortex that allows information to flow from the short to the long-term stores.

Turning to the second widely accepted model, that of SHY, this proposes that the main function of sleep is to restore synaptic homeostasis and therefore plasticity (Tononi & Cirelli, 2014). Otherwise, synaptogenesis and synaptic strengthening during development and learning would have serious consequences, both on cellular and system levels. Energy consumption would increase in line with cell stress due to the increased need for cellular supplies. Learning capacity could easily become saturated and selectivity of neural responses could decrease. SHY proposes that renormalisation should occur during sleep, as sleep allows the brain to obtain an overall picture of its general knowledge of the environment. During wakefulness, since the brain is occupied with the ongoing sampling of the environment, this process would be limited. The process of renormalisation is not entirely clear. Computational models of the theory have used different rules with the same outcome: an overall downscaling of synaptic strength with a competitive down-selection, resulting in some synapses becoming less effective than others (Hill, Tononi & Ghilardi, 2008; Nere, Hashmi, Cirelli & Tononi, 2013; Olcese, Esser & Tononi, 2010). In this way, the 'fittest' synapses survive: those that were strengthened repeatedly during wake or fit in well with old memories and the existing network. Tononi and Cirelli (2014) argue that the restoration of synaptic homeostasis is beneficial for cell energetics—optimising cellular supplies—and for memory. The restoration of learning capacity is crucial in order to be able to encode new information. Furthermore, consolidation benefits from synaptic downscaling. If weaker synapses and as a result memories are less active, there will be a better signal-to-noise ratio resulting in better recall. Similarly, integration can be explained through down-selection. If a new memory fits into a wider network, it becomes protected through being strongly co-activated during sleep alongside established, old memories.

Despite their wide acceptance and strong explanatory properties both models have been criticised. Tononi and Cirelli (2014) raised the issue that because the activation of episodic memories always involves the hippocampus as it indexes cortical representations (Winocur & Moscovitch, 2011), the transfer between short to long-term stores proposed by the ASC model is problematic. Furthermore, neocortical circuits may learn rapidly if a new memory can be easily integrated with related established knowledge (Tse et al., 2011). Another major point which the ASC model is unable to address is that it is not clear how the brain is capable of selecting the 'right replays' during sleep whilst being disconnected from the environment (Tononi & Cirelli, 2014).

Having said that, SHY is also unable to explain all the experimental findings as described in Rasch and Born (2013). During wakefulness, both LTP and long-term depotentiation (LDP) are present; as such sleep cannot be exclusively associated with LDP and wakefulness with LTP (Collingridge, Peineau, Howland & Wang, 2010; Kemp & Manahan-

Vaughan, 2007). Furthermore, it has been demonstrated in cats that evoked potentials were enhanced after SWS (Chauvette, Seigneur & Timofeev, 2012). Rasch and Born also highlight the fact that there is no experimental data supporting the claim of synapses being nullified via downscaling when under a certain threshold. Moreover, a wide range of studies suggest that weaker representations benefit more from sleep than stronger ones (Drosopoulos, Schulze, Fischer & Born, 2007; Ekstrand, 1967; Ekstrand, Sullivan, Parker & West, 1971; Fenn et al., 2003; Kuriyama, Stickgold & Walker, 2004). Finally, it is also true that the sleep-dependent reorganisation of memories is hard to explain within the SHY model, as this would involve downscaling for certain memories whilst upscaling for others (Rasch & Born, 2013).

Taken all of these findings together, it is clear that sleep plays an important role in many neurocognitive processes evidenced by a variety of experimental results. However, the exact nature of the underlying neurophysiological mechanisms has not been established. While the two most influential theories, ASC and SHY, can explain some of the experimental results, neither of them provides a comprehensive description of the underlying mechanisms of sleep-dependent neurocognitive processes. Memory reorganisation, which is crucial for language related processes, seems to be a major challenge for both models. In the next section, a review of the research findings related to language learning and sleep in adults and children is undertaken.

Sleep and language

Experimental designs using language are particularly suited to investigate sleep-dependent structural changes in memory, such as integration and generalisation, as learning a language involves acquiring a large number of regularities and rules from the phonological to the grammatical level. In this section, we provide an overview of the role of sleep in language related cognitive functioning in adults and children, focusing on generalisation and abstraction, in addition to word learning and integration.

Generalisation and abstraction in adults

Generalisation and abstraction have been observed in learning new phoneme categories, new phonotactic rules and predictive relationships between different words (Batterink, Oudiette, Reber & Paller, 2014; Fenn, Margoliash & Nusbaum, 2013; Fenn et al., 2003; Gaskell et al., 2014; Gomez, Bootzin & Nadel, 2006; Hupbach, Gomez, Bootzin & Nadel, 2009). In their pioneering work, Fenn et al. (2003) studied the effects of sleep on understanding a synthetic speech. Participants were first presented with computer generated consonant-vowel-consonant (CVC) words both in auditory and written form. During testing, after having listened to the word, the subjects were required to type it. As training and test stimuli contained different words, correct responses in the testing trials could only have been as a consequence of generalising the acoustic patterns of the language. For the group which slept after training a stabilising effect was observed, whereas for the group which had training in the morning performance deteriorated. However, after having had their night time sleep, their performance was restored. In a more recent study, the effect of sleep on rote learning and generalisation was compared using a similar paradigm (Fenn et al., 2013). The rote learning group received training for only 20 words and tested on the same 20, in addition to 100 novel words. By comparison, the training session contained 50 unique words for the generalisation group, while they were tested on 20 randomly selected from the previously heard 50, plus 100 novels. Regarding the training words, the performance of the rote training group improved remarkably after sleep, whereas an increase in performance of the generalisation group was much less robust. Nevertheless, sleep enhanced the recognition of novel words only in the generalisation group.

Gaskell et al. (2014) studied how sleep influences the integration of newly learnt phonotactic constraints. Phonotactic constraints are the rules of phoneme placements and their combinations in a given language. First-order constraints set the possible syllabic positions of a phoneme; while second-order constraints regulate which phoneme combinations are accepted. In this experiment, the learning of second-ordered constraints was examined. Participants had to read aloud CVC syllables in which two consonants were always in the same position within the syllable, the position of the other two consonants being depended on the vowel, while the position of the remaining consonants was unrestricted. Speech errors were analysed along with explicit memory of the syllables and a generalisation task. Those participants who had a nap after the syllable repetition task displayed the effect of the new constraints as reflected through their speech errors. The implicit effect on speech errors showed positive correlations with SWS and negatively correlated with REM and sleep duration. Participants who slept learned the new phonological distribution that became integrated with the existing distribution of English. Moreover, the nap group was better in explicitly applying the constraints to new stimuli, which suggests that they learned an abstract knowledge of the second-order constraints.

However, there are two studies which did not find an effect for offline consolidation on phonological learning (Eisner & McQueen, 2006; Roth, Kishon-Rabin, Hildesheimer & Karni, 2005). Earle and Myers (2014) emphasise that in these two studies the perceptual adjustments of phonetic category boundaries were made within pre-existing ones, therefore, it did not require new information to be added into, or any reorganisation of, the phonological system.

Nieuwenhuis and colleagues (Nieuwenhuis, Folia, Forkstam, Jensen & Petersson, 2013) investigated whether the facilitating effect of sleep on rule extraction is also apparent in the case of an artificial grammar learning paradigm. During the testing phase, participants had to classify novel sequences as grammatical or agrammatical. After sleep, the performance on the task was better due to facilitation through having extracted the underlying rule, as opposed to detecting parts of the presented sequences. The enhancing effect of sleep on learning a linguistic rule was also confirmed by Batterink et al. (2014) in an experiment in which participants were exposed to two-word phrases: the second word was a known English noun, while the first was a pseudoword that used one novel word out of four possibilities and served as an article. Participants were told that the novel words also incorporate how far the referent was, with two words meaning 'near', the other two meaning 'far'. However, there was also a hidden rule, unknown to participants, in which the novel words predicted the animacy (i.e. how alive the referent is) of the noun. During testing, participants had to decide whether a phrase was inanimate or animate. If they learnt the hidden rule, their reaction time was slower when the phrase violated that rule. After an afternoon nap, those participants who had had more SWS and REM showed an increased sensitivity to the hidden rule, even if they remain consciously unable to define it.

Generalisation and abstraction in infants

Similar results were found in 15 month old infants (Gomez et al., 2006). Infants were presented with word strings generated from an underlying rule in which the first word predicted the third. Testing followed after four hours using the head-turn preference procedure (Fernald, 1985). After a nap, infants were able to generalise this knowledge to novel, previously not heard stimuli, as they listened longer to sentences that had the same predictive pattern as the first post-sleep trial type. In contrast, the wake group listened longer to those sentences that followed the same rule as the training stimuli (Gomez et al., 2006). Moreover, these results were also replicated by Hupbach et al. (2009), who found that this effect to be long-lasting, as was apparent during testing on the next day, but only for the nap group. Having said that, contradictory results were also found, though in a slightly older age group of 2.5 year olds (Werchan & Gomez, 2014). Children learnt labels for three novel categories of objects presented on different backgrounds. During testing, four objects were shown in a trial: a new exemplar of the novel category, a distracter, a novel and a familiar object. Children were asked to point to the new exemplar using the label for the category. In addition to the nap and the wake group, an immediate testing group was also included. There was no sign of generalisation in the immediate testing group or in the nap group (tested 4 hours after training and having taken a nap) as children performed correctly in less than 50% of the trials. However, those children who did not nap between training and testing were able to generalise the category's label to new exemplars. The authors argue that forgetting of irrelevant information is crucial for generalisation. They also claim that sleep might have strengthened both the relevant and irrelevant features of the category, thus impaired generalisation. Gomez and Edgin (2015) proposed that these results reflect a developmental shift in memory processes. They argue that only over 18 month of age, when the hippocampus matures, can sleep have a facilitating role in the consolidation of hippocampal memories. Therefore, results in 15 month olds reflect non-hippocampus dependent, cortical memory processes that is less able to code precise information.

Taken together, the above findings suggest that sleep has an impact on generalising memories and extracting abstract rules which are crucial in acquiring a language, although results are controversial regarding which sleep stages are relevant for these processes and whether the association shows a developmental pattern.

Word learning and integration in adults

The other line of research on sleep-dependent language related processes is concerned with how new words can be integrated into the mental lexicon. Gaskell and Dumay (2003) developed a research design which is able to detect lexicalisation of new word forms. Fictitious words that overlap with existing ones are taught to participants (e.g. cathedruke – cathedral). New words were chosen in such a way that if they became integrated to the mental lexicon the word's uniqueness point (the point at which the acoustic-phonetic information already presented corresponds to only one lexical entry, Radeau & Morais, 1990) shifts to its final vowel. They measured explicit recall with the two-alternative forced choice (2-AFC) task in which participants had to choose the newly learnt words from foils (e.g. cathedruke and cathedruce). Participants showed good recognition performance immediately after learning and remained at the same level for five days. To assess lexicalisation, a lexical decision task (in which participants have to decide whether the presented word is a real word) was used with the base words and fillers, and responses were timed. If a new word has become integrated into their lexicon, responses to their phonological neighbours will slow down due to lexical competition. During immediate testing participants did not show lexical competition, but rather a facilitatory effect was observed. However, there was a significant inhibitory effect from the second day of testing, which became most prominent on days 4 and 5. These findings were confirmed with a pause detection task that had previously been shown to be an effective tool for assessing lexical activity (Mattys & Clark, 2002), due to the fact that listeners are slower in pause detection when the word has a late uniqueness point. An important advantage of using this task is that this way is that participants are not exposed to the new words from day 2, therefore repeated exposures cannot affect the time course of lexical inhibition. One week after the initial learning, lexical inhibition developed, indicated by an increased reaction time in the pause detection test (Gaskell & Dumay, 2003). The results of these three experiments suggest that lexicalisation develop gradually with off-line consolidation. However, these experiments were not concerned with acquiring the meaning of the new words, which is clearly important for word acquisition in non-laboratory environments. Therefore, it was an important finding of research conducted by Dumay, Gaskell and Feng (2004) who found that providing a meaning and the sentential context for words did not affect the results. Furthermore, they showed that lexicalisation took place in the first 24 hours after the first exposure (Dumay et al., 2004). As a next step, Dumay and Gaskell (2007) studied whether it is only time that is necessary for lexicalisation, or whether the off-line period should contain sleep. For this, they compared two groups, in which one had their training session in the morning, the other one in the evening. Explicit memory for the 2-AFC recognition and free recall, and lexical activity with the pause detection task, were tested immediately, and 12 and 24 hours following training. Importantly, lexical competition was only apparent after sleep, suggesting that sleep is needed in order to integrate new word forms into the mental lexicon. In addition, free recall also improved after sleep; although it is not clear whether it reflects the strengthening of episodic memories or due to the generation of new lexical entries (Dumay & Gaskell, 2007). More recently, it was shown that sleep spindle activity correlated positively with the overnight change in lexical integration, while this association was not apparent for recall or recognition speed (Tamminen, Payne, Stickgold, Wamsley & Gaskell, 2010), suggesting the central role of sleep in the lexicalisation process. Nevertheless, in this experiment, lexical competition also occurred after waking. To explain the lack of differences in the wake and the sleep group, the authors speculate that some degree of consolidation can take place in a wakeful state, especially if the training is not conducted in one session, but distributed over a day (Lindsay & Gaskell, 2009). Participants may have practised the words during the day, which could have resulted in the above findings (Tamminen et al., 2010).

The enhancing effect of sleep on integration of new words is further supported by experiments using different types of designs. Tamminen, Lambon Ralph and Lewis (2013) studied which sleep components mediate the integration of novel words with dense or sparse semantic neighbourhood density (i.e. how many associates a word has). Four tasks were used to measure speeded access for the novel words and concepts (animacy decision, synonym judgement, a reading aloud task and a progressive demasking task in which a trained word was presented interspersed with a masking stimulus and the duration of the masking stimulus decreased gradually) with reaction times being monitored. Participants were slower on three out of four tasks when they had to respond to words with high semantic density—suggesting that the word became integrated, and that the related neighbours caused interference. In the animacy decision task, sleep was necessary in order for this effect to be observed. Furthermore, there was increased sleep spindle activity and a trend towards higher SWA after learning words with sparse semantic density. The authors argue that integration into a sparse neighbourhood is more rapid as inconsistent knowledge is less likely to be present (Tamminen et al., 2013). However, it is not clear why this would lead to higher spindle activity. Differences in encoding is unlikely because there was no difference in explicit recall tests. As has been shown, consolidation is more efficient if there are more representations in a network (Tse et al., 2007); it is also possible that consolidating to a sparse semantic neighbourhood is more difficult.

Sleep-dependent integration was also supported by a study using speech segmentation as the manifestation of lexical engagement (Dumay & Gaskell, 2012). Two types of stimuli were investigated, one where the word shared its beginning with a pre-existing real word ('frenzylk'), the other one where the new word was fully embed an existing real word ('lirmucktoze'). In addition to the pause detection task, a word spotting task that required lexical segmentation was used. As new words become integrated embedded words become harder to spot, as they are lexically compatible. After a sleep a significant inhibition emerged in both tasks, although the inhibition in word spotting for fully embedded stimuli was stronger.

Tham, Lindsay and Gaskell (2015) investigated whether automaticity in accessing newly learnt word meanings due to integration was associated with sleep. They used two paradigms with animal names, namely: size congruity and semantic distance. In the size congruity paradigm participants respond faster if the relative sizes of the referents are congruent to the font size (e.g. COW – bee). In semantic distance paradigms, judgment of the relative sizes is faster if the size difference is larger (e.g. bee – cow versus dog - cow). Two experiments were carried out, in the first of which native English speaking participants had to learn Mandarin words, whilst in the second they learnt Malay. After sleeping, participants showed greater automaticity measured with the size congruity effect, which was not apparent after remaining awake. Moreover, this effect correlated positively with the number of sleep spindles. However, the semantic distance effect was also observable after remaining awake, even though sleep enhanced it. This effect correlated with SWS. The authors argue that the semantic distance effect is a weaker measure of automaticity because it does not require the processing of the physical properties of the written text. Tamminen and Gaskell (2013) used semantic priming to assess integration in which participants took part in a lexical decision task for familiar words. Familiar and novel words did not co-occur in training, therefore direct associations between the words did not confound the results. Integration was the strongest a week after learning, although results did not reach statistical significance.

Results from an fMRI study further support the finding that sleep facilitates integration of new words and underline the dual-learning system hypothesis (Davis, Di Betta, Macdonald & Gaskell, 2009). For pseudowords, a strong bilateral activation of the superior temporal gyri was observed. In addition, the inferior frontal, premotor and motor cortices and the cerebellum were also active, which might be a reflection of increased phonological processing. Moreover, the activation pattern did not change during the day even if repeated familiarisation occurred. However, after sleep the activation pattern for the pseudowords learnt the day before was similar to familiar words.

Word learning and integration in children

Similarly, as with adults, some studies on children showed that for stabilising new phonological representations, offline consolidation is beneficial. Consolidation of novel phonological forms benefited from a 24 hour period containing sleep in 7 and 12 year old children. After training, recall of newly learnt words was poor but improved after 24 hours. In contrast, recognition performance was accurate right after learning (Brown, Weighall, Henderson & Gaskell, 2012). Henderson et al. (2012) made the clarification that not just offline consolidation is needed for the enhanced consolidation, but a period of sleep. Moreover, they showed that in 7-12 year olds lexical competition only developed after sleep. Furthermore, word recognition and recall were also enhanced as a consequence of sleeping. Interestingly, there was a decline in children's retention of object-pair locations (declarative memories) during the day, which was not apparent after sleep, suggesting that learning words has a different off-line consolidation pattern from declarative memory consolidation (Henderson et al., 2012). In another study, the importance of providing the meanings of the words was shown (Henderson, Weighall & Gaskell, 2013). 5-9 year olds were taught words with or without their meanings. Children showed increased recall after sleep, but those children who were also exposed to the meanings showed further improvement after one week, and had a better performance than the other group. Interestingly, the lexical competition effect weakened over the course of a week in both groups; although competition effects were numerically, but not statistically, stronger in the semantic group. The authors claim that these findings may be the results of the increased variability in the performance on the pause detection task. Another research group also found the positive effect of sleep on word learning (Ashworth, Hill, Karmiloff-Smith & Dimitriou, 2014). Ashworth and colleagues used an animal name learning task to study the impact of sleep on learning in 6-12 year old children, in which they also found that after sleep children improved significantly in recalling animal names. Taken together, these results suggest that children benefit from sleep on highly controlled word learning tasks.

The above findings were also supported by research using a more naturalistic setting for learning (Henderson, Devine, Weighall & Gaskell, 2015; Williams & Horst, 2014). Henderson et al. (2015) who, using stories as a less explicit learning task, found that sleep facilitated both the recall and integration of words. An additional outcome of their research being that the productive vocabulary size of children was associated with larger consolidation effects.

Williams and Horst (2014) studied how sleep influences learning new words from stories by having 3 year olds read stories with two new target words. Half of the children heard one story three times, the other half heard three different stories. Those children who regularly napped slept in the nursery after training, non-habitual nappers remained awake. Repeated readings had a positive impact on word learning in both the nap and the no-nap groups. In addition, daytime sleep also helped to consolidate words in the condition where different stories were read to the children. These two studies demonstrated that sleep-dependent consolidation is also apparent in tasks which are closer to the way of learning in children outside laboratory settings.

Word learning and integration in infants

In infants, only one study has so far examined how sleep influences word learning (Friedrich, Wilhelm, Born & Friederici, 2015). Friedrich and colleagues conducted an experiment assessing picture-word priming effects using event-related potentials (ERP) in 9-16 month old infants. In the training session, three conditions were presented: in the consistent object pairing condition, one object always appeared with one label; in the consistent category pairings condition, one label corresponded to more, similar objects that formed a category; in the inconsistent pairings condition, one label corresponded to more than one different object. In the test session, correct object pairings and incorrect object pairings were presented; as well as correct novel category pairings and incorrect novel category pairings—in which the novel category corresponds to a new exemplar of the categories. In the training session, initial learning of specific word meanings was implied by a late negative component that was not previously described. The authors argue that the demanding nature of the task could be the reason behind this. For category learning, no effects were shown on the ERP, possibly indicating the acquisition of the name of the category. Those infants that did not nap after training showed no sign of remembering specific word meanings or generalisation of labels to new category exemplars. In contrast, after a nap the N200-500 component increased in the correct object pairing condition compared to the incorrect object pairing condition, indicating that the novel word meanings were transferred to long-term memory. However, because similar effects were not observable in the N400 component, there is no evidence for semantic representation (i.e. the neural representation of the meanings of the words). On the other hand, N400 decreased in the correct novel category pairings condition compared to the incorrect novel category pairings condition, indicating integration into new semantic representations. Furthermore, EEG power in the sleep spindle frequency range correlated with the N400 priming effect, but not with the N200-500 component.

Complementary learning systems framework and the association between language learning and sleep

Findings regarding word learning can be explained by the complementary learning systems (CLS) framework (Davis & Gaskell, 2009; McClelland, McNaughton & O'Reilly, 1995). The CLS incorporates the computational properties of neural networks with neurophysiological findings and proposes two distinct memory systems similarly to other dual memory system models. Briefly, the model describes a system for unique, context specific memories represented sparsely, and another system for overlapping semantic representations in which a generalised knowledge is stored. During off-line replay, information is being transferred from the first system to the second. The CLS is in line with the ASC hypothesis, therefore language related results can be explained within the framework of general memory systems (Davis & Gaskell, 2009), especially considering that the associations between sleep and non-language related neurocognitive functions are fairly similar.

As we have seen in Sections 1 and 2, while there is a wealth of evidence for the beneficial role of sleep to neurocognitive function in adults and some in children, the relationship is rather under investigated in infants. Nevertheless, there are dramatic changes both in sleep and language development in the first two years of life, which might imply a stronger association. Moreover, beyond theoretical interests, a link between sleep and language would have practical implications for ensuring and enabling healthy language development.

Language development

First and foremost, it is important to appreciate the pace at which language develops in infants. In the first two years of life language develops dramatically. From a babbling 6-9 month old infant, the child becomes able to produce complex sentences at around 2.5 years (Harley, 2008). Infants acquire the sound structure of their native language by 6-12 months (Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992). Around this age, they are also able to recognise frequent word forms (Jusczyk & Hohne, 1997). They utter their first words just before their first birthday. By around 18 months there is a huge expansion in vocabulary size, referred to as the vocabulary spurt, at which point they start to use two-word speech. From around 2 years, children begin to acquire the grammar of their native language, which continues throughout childhood (Harley, 2008).

Throughout the rest of this section we concentrate on word learning, as this has a crucial place in the rapid pace of language development, as it may help to learn phonetic categories, to develop the mental lexicon, and to acquire grammatical structures (Swingley, 2009).

Familiarity with word forms was shown in the study carried out by Jusczyk and Hohne (1997) in which 8 month old infants were read story books several times over a two-week period. The infants were tested using a head-turn preference procedure, which is a commonly used method to assess language learning in infancy. Children preferred to listen to words that had been previously read to them in the stories, meaning they remembered specific words. Even younger infants of 4.5 months old showed preferential listening to their own names (Mandel, Jusczyk & Pisoni, 1995).

Although these results suggest that infants are able to remember a word form at early ages, they do not provide information on whether they actually understand what the words mean. Early experimental studies showed that 13 month olds understood word meanings, whereas 11 month olds did not, although the experimental design may have been too complex for the younger age group (Swingley, 2009). Tincoff and Jusczyk (1999) demonstrated that when 6 month olds heard mummy or daddy the infants looked more at the parent named compared to the unnamed one. However, this was only true in the case of their own parents, indicating that they linked the words to their parents and did not have a general knowledge of the word meanings. On the other hand, Bergelson and Swingley (2012) using body parts and food in a preferential looking paradigm, found that 6-9 month olds understood many of the words. Importantly, they did not use pre-recorded audio stimuli, but the parents were asked to repeat sentences that they were played through headphones. Every object appeared three times during the experiment and in each case a different picture was presented. This suggests that infants were able to generalise both the meanings of the nouns and the phonological pattern of the words. Parents were not able to see the pictures, thus they could not unintentionally direct their infants' look in the direction of the correct picture. These results have recently been replicated (Bergelson & Swingley, 2014). Again, methodological issues greatly influence the outcome of word learning and word comprehension experiments.

Social, communicative aspects of word learning are of importance because data suggest that word learning is better in social context (Baldwin, 1991; Baldwin et al., 1996). Many authors claim that infants should be able to understand the intentions of the speaker to find what the word refers to (Tomasello, 1992). Carpenter, Nagell and Tomasello (1998) followed children between 9-15 months of age and tracked the development of joint attentional engagement, gaze and point following, imitation, gestures and language comprehension and production. They found that two measures were correlated with language skills and gestures:

the amount of time the infants spend in joint engagement with their mothers and the degree to which mothers used utterances to follow into the infant's focus of attention. The beneficial effect of joint attention to word learning was also found in a more recent ERP study (Hirotani, Stets, Striano & Friederici, 2009). 18-21 month olds were taught new words in two contexts, a joint attention context and a non-joint attention context. Eye contact and the tone of voice were manipulated between the two conditions. ERPs of congruent and incongruent picture-word pairs were compared. While an early negativity was apparent in both conditions, suggesting that the toddlers acquired the phonological word form, for the incongruent word-picture pairs, an N400-like effect was observable but only for the joint attention condition, reflecting semantic knowledge.

The phase of language development in infancy referred to as the vocabulary spurt corresponds to a sudden increase in the rate of word acquisition between 18 and 24 months of age (Bloom, 1973), although the reasons behind it have not yet been delineated. One major line of reasoning and research claims that there is a maturational change in the brain or the acquisition of certain cognitive skills. However, another line of research explains that in terms of the statistical properties of linguistic material. Naming insight was one of the first proposed maturation changes behind the vocabulary spurt (Kahmi, 1986). That is, when infants understand that words refer to things and that every object has a name, instead of remembering associations between objects and word forms, acquisition speeds up (Nazzi & Bertoncini, 2003). Furthermore, change in categorisation abilities has also been suggested to be one of the factors behind the vocabulary spurt (Nazzi & Bertoncini, 2003). Better word segmentation (Plunkett, 1993) may be another reason for the increased pace. Moreover, Mills, Coffey-Corina and Neville (1997) compared 13 and 20 month olds in an ERP study in which the infants listened to words that they were or not familiar with, and words spelt backwards. In the younger age group, the differences related to word comprehension were spread out over both hemispheres. However, older children showed specialisation, as the effects occurred in the left temporal and parietal cortices. In another study, Mills and colleagues (Mills, Plunkett, Prat & Schafer, 2005) contrasted the ERPs for newly learnt words between 20 month olds with low and high expressive vocabularies. Those who had larger production score showed a more specialised brain response, suggesting more efficient word processing as a result of the left hemispheric specialisation. Development of memory processes may also be an important factor in the vocabulary spurt. Gomez and Edgin (2015) proposed that between 18-24 months is the age when the hippocampal circuitry matures and can promote fast encoding. In addition, after this age sleep facilitates precise consolidation of new memories compared to the younger age group, in which sleep seems to have a generalising role. The other hypothesis explains the vocabulary spurt strictly in terms of the statistical properties of language, claiming that some words are more difficult to learn (McMurray, 2007). However, Mayor and Plunkett (2010) showed that word frequency cannot be the only cause of the acceleration.

Many studies showed that infants are able to learn new words under laboratory conditions, even before the vocabulary spurt. For example, Woodward, Markman and Fitzsimmons (1994) found that 13 month olds could learn words quickly after only nine repetitions. However, in this study only one object was named during the familiarisation period. Thus, although object preference was controlled for with preference trials without any naming, we cannot draw any inferences as to whether the infants associated the target object with the naming itself or whether they also remembered the word form. Schafer and Plunkett (1998) therefore used two object – label pairs with 15 month old infants in an experiment in which learning was assessed by the intermodal preferential looking (IPL) task. In this task, the target object is simultaneously presented with a distracter and the target is labelled. Studies differ in the specific looking variables analysed, but the basic idea is that if infants understand the label, they show some kind of preference to the target. Object saliency may alter the results, hence it is often controlled for. Schafer and Plunkett found that after 12 repetitions, infants were able to learn—as indicated by the longest look—which they claim to be the most robust sign of target preference. Schafer (2005) showed that even younger, 9 and 12 month old infants can learn new words. Pruden and colleagues (Pruden, Hirsh-Pasek, Golinkoff & Hennon, 2006) also confirmed this in 10 month olds: infants were able to learn some of the words after five exposures. In addition, they suggested that word learning in 10 month olds is driven by the saliency of the objects in contrast with to social cues offered by the speaker.

Most of the studies concentrate on encoding and are less concerned with consolidation (Wojcik, 2013) or about how the words are organised in the brain in infancy (Gaskell & Ellis, 2009). In order to investigate the associations between words, Arias-Trejo and Plunkett (2009), used a modified version of the IPL paradigm, in which infants were presented with a prime and a target word just before the infants were shown two pictures, the target and a distracter. 18 month olds did not show increased target looking in the related prime condition compared to the unrelated condition, even though they responded to the target in both cases. In addition, they did not distinguish between the target and distracter when the target was not named. On the other hand, 21 month olds were unable to identify the target if they heard an unrelated prime, suggesting interference. However, they increased their looking at the target in the related condition. These results indicate that at 21 months of age there are semantic and associative links between word representations, thus one can conclude that the mental lexicon has developed (Arias-Trejo & Plunkett, 2009). In contrast, younger infants store separate and unconnected representations of lexical concepts (Gaskell & Ellis, 2009).

In order to be able to integrate a word into the lexicon, consolidation is necessary. Bauer (2005) showed that there is a developmental trajectory in consolidation even if the equivalent encoding is ensured in different age groups. After reviewing the literature, Wojcik (2013) concludes that there are various factors which can lead to successful memory consolidation.

She also highlights that this is also true for word learning. For example, Booth (2009) showed that consolidating a word is more successful if 3 year olds are taught with the causal properties, even though it does not affect initial encoding. Importantly, as we reviewed in the previous section, sleep has an impact on consolidation which may be dependent of age (Gomez & Edgin, 2015; Wojcik, 2013).

Sleep development

In the last section of this Introduction, we aim to show that the dramatic development in the first few years is not exclusive to changes in language ability, but the duration and timing, the architecture, and the EEG components of sleep also change with age.

Sleep duration, number of awakenings and number of daytime naps decrease with age. A meta-analysis (Galland, Taylor, Elder & Herbison, 2012) of 34 studies found the most rapid decline (10.5 min/month) between 1-6 months, which slows down between 7-12 months to 5.4 min/month. Between 1 and 4 years the rate of the decline is about 7.8 min/year. Interestingly, the comparison of studies from predominantly Asian countries/region and from predominantly Caucasian/non-Asian countries revealed almost an hour shorter duration in the former. In addition, in children who were born later, a decreased sleep duration was found (Iglowstein, Jenni, Molinari & Largo, 2003). Despite the age dependent change in sleep variables, there is a remarkable long-term stability in children in terms of sleep duration, suggesting that there are trait-like characteristics in intra-individual variability (Jenni, Molinari, Caflisch & Largo, 2007). Similarly, there was a decline in the number of night awakenings, although data was highly variable. Furthermore, the number of daytime naps drops from around 3.5 naps/day at 1 month to 1 nap/day at 18 months. Because the cross-cultural comparisons did not reveal any differences, the authors claim that this sleep measure is more biologically determined as opposed to being subject to cultural influences. At the same time, the longest sleep period increases from about 5 hours/night at 1 month to 8.5 hours at 18 months (Galland et al., 2012).

In the early years of life, sleep consolidation takes place during which there is a transition from polyphasic to biphasic sleep pattern. Instead of multiple naps per day, there is one nap and a dominant night time sleep period. This phenomenon may be the consequence of the reducing influence of sleep pressure with development and more pronounced circadian regulation (Peirano, Algarin & Uauy, 2003). Between 2 and 5 years, night time sleep becomes predominant without habitual naps during the day. El-Sheikh and colleagues (El-Sheikh, Arsiwalla, Staton, Dyer & Vaughn, 2013) report many studies which showed an inverse relationship between the length of nap duration and sleep duration. However, the findings of El-Sheikh et al.'s study did not confirm these results. Nevertheless, they showed that sleep quality, assessed by the number of awakenings and activity during sleep, was highly correlated between daytime naps and night time sleep, indicating a trait-like effect in sleep quality (El-Sheikh et al., 2013).

The architecture of sleep also goes through development in early ages. In a newborn, the immature forms of REM and NREM sleep are present: active and quiet sleep along with an intermediate form. Active sleep consists of mixed frequency oscillations with relatively lower amplitude. It occurs at sleep onset until 3 months of age. Mainly a low muscle tone is characteristic, but rapid bursts of eye movements, and some phasic movements and twitches are also observable. On the other hand, quiet sleep is characterised by continuous, high amplitude delta activity with sleep spindles. The muscle tone is moderate and breathing is regular (Lee & Rosen, 2012). If the sleep epoch does not meet the criteria of either of the sleep stages or of being awake, it is coded as intermediate sleep. Because all the polysomnographic characteristics of REM sleep are present at the age of 2 months, the use of REM and NREM sleep has been suggested after this age (Grigg-Damberger et al., 2007). The distinction between different NREM stages are only possible from around 3-6 months. In the newborn, active sleep is 60-70% of the total sleep time, but in the first few months, quiet sleep becomes predominant (Lee & Rosen, 2012). This is due to the shortening of the active sleep period and the lengthening of the quiet sleep period. The length of the sleep cycles does not change in the first year of life but it remains around 60 minutes. The adult cycle length of 90 minutes is reached between 2-6 years—the exact age is unknown (Jenni, Borbely & Achermann, 2004).

We know less about the ontogenesis of the composition of the sleep EEG. Jenni et al. (2004) reported a general, sleep stage independent increase in spectral power in the first 6 months, especially in the lower frequency EEG bands. This observation may be the result of the increased synaptic connectivity and the myelination of the white matter. In contrast with adults, active and quiet sleep only differs in the low frequency delta components (0.75-1.75 Hz), with higher delta power (2-6.25 Hz) being similar in the two stages. This might also indicate functional differences of the different frequency components of the delta band. In addition, a peak between 12-14 Hz emerged around 2 months on the EEG spectrum in quiet sleep, indicating the occurrence of sleep spindles. It is interesting that in terms of sleep EEG dynamics during sleep, only theta band (6.5-9 Hz) showed a decline within a sleep episode from 2 months onward. This decline resembles the decrease in delta, theta and alpha power in adults within a sleep episode that is linked to sleep homeostasis. It is interesting that in infants only the theta band shows this reduction, and the delta band does not seems to be coupled to this mechanism (Jenni et al., 2004). However, Fattinger and colleagues (Fattinger, Jenni, Schmitt, Achermann & Huber, 2014) used a different measure—the slope of sleep slow waves—in their longitudinal study that showed homeostatic regulation. In all age groups tested (2-9 months) the slope decreased from the first to the last hour of NREM sleep. The steepest slope was found over the occipital cortex. The authors claim that the intensive synaptogenesis over the occipital cortex explains why the steepest slope was the most pronounced in that area.

Scholle, Zwacka and Scholle (2007) identified three distinct phases in sleep spindle development in childhood. Classical spindles can be identified from around 1 month post-term, and it is present in all infants at 2 months. They can be detected in two different locations, in two different frequency ranges: slow spindles over the frontal areas with 11-12.75 Hz, and fast spindles over the centroparietal areas with 13-14.75 Hz (Grigg-Damberger et al., 2007). Spindle length and spindle density followed a U-shape association with age. In the first developmental stage, up to around 10 months, spindles are the longest, whereas spindle density is low. Between 10 months and 3 years, there is a decrease in spindle length, but spindle density does not change remarkably and remains low. Up to the age of 11 years spindle density increases substantially, similarly to spindle length. It is important to note that sleep spindle variables show a high inter-individual variability (Scholle et al., 2007). Most of the spindles are asynchronous between the hemispheres in infants under 2 years (Grigg-Damberger et al., 2007). The developmental changes may indicate the maturation of the thalamocortical circuits (Scholle et al., 2007).

Taken together, many different aspects of sleep show a developmental trajectory which is particularly intensive in the first year of life, but which is still substantial in toddlers and continues to develop up to adolescence. The disparate architecture of sleep in infancy may provide us with an opportunity to investigate whether the associations between sleep and language is similar to that in adults. Furthermore, it may also shed light of the role of different components of sleep.

Overview of the thesis

The major aim of this thesis is to increase our understanding of the sleep–language connection in infancy, particularly regarding word learning, generalisation of word meanings and vocabulary development. We used two main approaches to investigate the connection. The first approach uses cross-modal designs to show how a nap can influence language learning, whereas the second approach is a longitudinal one to see whether vocabulary can be predicted from different sleep variables. In Chapter 2, a word learning paradigm which is sensitive enough to show word learning in infants in a laboratory environment will be outlined, in which two abstract object-pseudoword pairs in the interactive play and on-screen training session are used. Looking behaviour in an IPL paradigm was monitored with automated eye tracking. In Chapter 3, this paradigm is extended with a second testing session after a nap for the nap group and a period of wake for the no-nap group. This way, we were able to investigate how a nap influences word learning. It is hypothesised that a nap would be beneficial for learning novel words. In Chapter 4, a study of how a nap influences the generalisation of a newly learnt word form to similar objects is outlined. Chapter 5 provides normal data on the sleeping patterns of infants and toddlers, collected with the aid of a newly designed sleep diary. We also studied some of the factors which have an impact on sleeping. In Chapter 6, it is demonstrated how sleeping variables predict vocabulary development in the first three years of life. Finally, the results of the five studies in the context of the literature is discussed in Chapter 7.

CHAPTER 2. RAPID WORD LEARNING IN 14 MONTH OLDS

Studying word learning in infancy is a challenging task due to different methodological issues influencing the results. Thus, before investigating the effects of napping on word learning, we conducted a pilot study to test whether infants were able to learn novel words under this research design and whether the methods used were sensitive enough to show word learning. Thirty-eight 14 month old infants were taught two novel object-word pairs and tested using the intermodal preferential looking (IPL) task with automated eye-tracking. Infants showed target preference, suggesting they learnt the novel object-word mappings.

Introduction

Word learning has a central role in language development as it supports the acquisition of phonetic categories, the development of the mental lexicon and the learning of grammar (Swingley, 2009). While it is clear that infants are able to learn words during their first year of life (see Chapter 1), demonstrating this under laboratory conditions has its own challenges. In this study, the aim was to test whether our research design is able to facilitate rapid word learning in 14 month old infants.

Comprehension of a word is often tested with the IPL paradigm (Golinkoff, Hirsh-Pasek, Cauley & Gordon, 1987) that has been validated against other language measures, and it may be even more sensitive than parental reports (Golinkoff, Ma, Song & Hirsh-Pasek, 2013). In this experimental design, children are seated in front of a large split screen or two smaller screens with two pictures visible with the auditory stimulus matching one of the objects displayed. The infants' looking behaviour is monitored either with a video camera or an eye-tracking device. In order to study novel word learning, training trials are introduced in which a single image is displayed with the corresponding audio, such that children are able to learn the new object-label association. To facilitate the learning process, our experimental design included an interactive learning session at the start of the experiment—previous research having shown that the social context during learning may help in the acquisition of new words (Baldwin, 1991; Baldwin et al., 1996). For example, the facilitating effect of joint attention to word learning has been demonstrated in a broad range of studies (Carpenter et al., 1998; Hirotani et al., 2009).

In other research, word learning has been investigated under laboratory conditions. For example, Woodward et al. (1994) showed that 13 month olds are able to learn new words after nine repetitions. Similarly, Schafer and Plunkett (1998) found that 15 month old infants were able to associate a label with an object after 12 repetitions—using two object-label pairs to ensure that infants would not only remember the labelling, but could correctly recognise the exact word form corresponding to the object.

In this pilot study, the aim was to develop a research design that is capable of showing word learning in pre-vocabulary spurt infants. To facilitate learning, an interactive play session was also included. We hypothesised that 14 month old infants are able to learn new words after 13 repetitions.

Methodology

Participants

Thirty eight infants were tested at the age of 14 months. All infants were from homes where English was the only language used. Prior to arrival parents were asked to complete the Oxford CDI to obtain vocabulary measures. Upon arrival written inform consent was collected from the caregiver and parents were asked about when their infants had woken up from their preceding nap or sleep.

Procedure

The study design and the script used in the playing phase were partly adapted from the study of Mani and Plunkett (2008). First, an interactive playing phase took place, followed by the first then the second blocks of on-screen training and testing.

During the interactive playing phase, infants sat on the caregiver’s lap or on the floor whilst the experimenter introduced each new object one at a time. Infants played with and observed the toys, while the experimenter verbally labelled each object nine times using the following template sentences: *“It’s a X!”, “Look! X!”, “The X does this.”, “Do you want to play with the X?”, “Can you say X?”, “Can I have the X?”, “Ooh, look! Where is the X?”, “Here is the X.”, “Show mummy the X!”*

The order of presentation of the objects and the object–label pairings were counterbalanced across the infants.

The play session was followed by an on-screen training and testing phase, during which infants sat on the caregiver’s lap approximately 80 cm from the screen and eye-tracker. Before presentation of experimental stimuli, a nine-point calibration (a beach ball appeared in nine different positions on the screen) was conducted, with individual calibration points repeated until four good calibrated points were obtained so the eye-tracker could identify the location of infant visual fixations. The duration of each trial was 5000 ms and they were initiated manually by the experimenter to assure the infant paid attention to the screen. Each trial was separated by a 1500 ms animation appearing in the centre of the screen to direct the attention of the infants towards the middle. At the beginning of each trial an attention getter sentence was played. During training, first a block of two familiar word trials (1x dog and 1x book, with the corresponding label) and then a block of four novel word learning (2x *tesh* /tɛʃ/ and 2x *ginn* /gɪn/) trials were presented. The presentation of the trials was randomised within each block. The visual stimulus appeared either on the left or the right side of the screen, the other side was left blank (the side of the novel objects was counterbalanced within infants). The label was spoken twice during each trial, the first onset was at 1500 ms and the second at 3500 ms.

The first block of testing trials followed immediately after training; first two familiar objects, then four novel objects (2x *tesh* /tɛʃ/ and 2x *ginn* /gɪn/) were tested. The timeline of the testing blocks can be observed in Figure 2.1. The presentation of the trials within the familiar and the novel block was randomised. Two pictures appeared simultaneously on the left and the right side of the screen (the side for the novel trials was counterbalanced within infants). The onset of the audio token was at 2500 ms. The novel objects were tested against each other. The six on-screen training and the six testing trials were immediately repeated once more with the same novel stimuli and with different familiar stimuli (1x shoe, 1x car, with the corresponding label). Familiar word learning trials were included to alleviate the repetitiveness of the study.

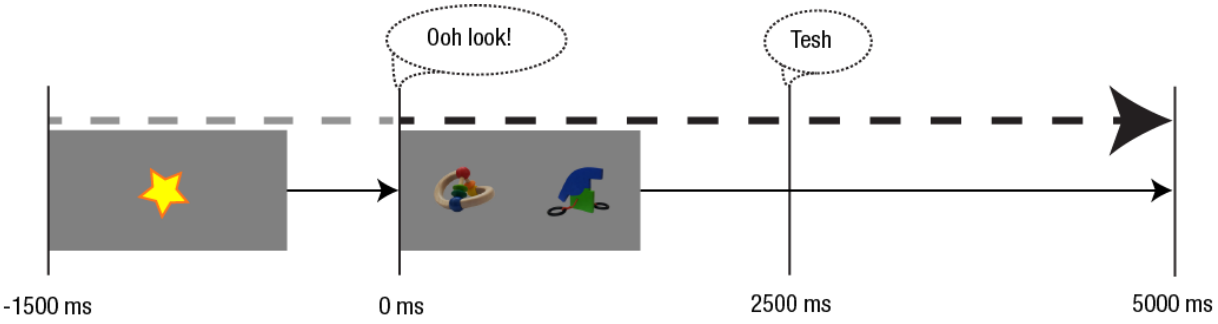

Figure 2.1. Timeline of the test trials

Stimuli

During the play phase, the infants were presented with two novel objects (Figure 2.2) each of which was named nine times by an experimenter with the labels (*tesh* /tɛʃ/ and *ginn* /gɪn/). During the on-screen training and testing phase infants saw coloured photographs of the trained objects plus four extra pictures (dog, book, shoe and car) were shown to alleviate the repetitiveness of the study. The pictures were 1024x768 pixel colour photographs presented on a 50% grey background on a 1920x1080 pixel 58 cm thin film transistor (TFT) monitor.

The audio stimuli consisted of two pseudowords (*tesh* /tɛʃ/ and *ginn* /gɪn/, at durations of 702 ms and 652 ms respectively), four familiar nouns (*dog*, *book*, *shoe* and *car*) and three attention phrases (*Ooh look!, Hey wow!, Look!*) produced by a female native speaker of British English in a southern accent. Audio stimuli were recorded in a sound-attenuating room with a solid state recorder sampling at 44.1 Hz in 16 bit stereo and were delivered through two speakers centrally located above the screen.

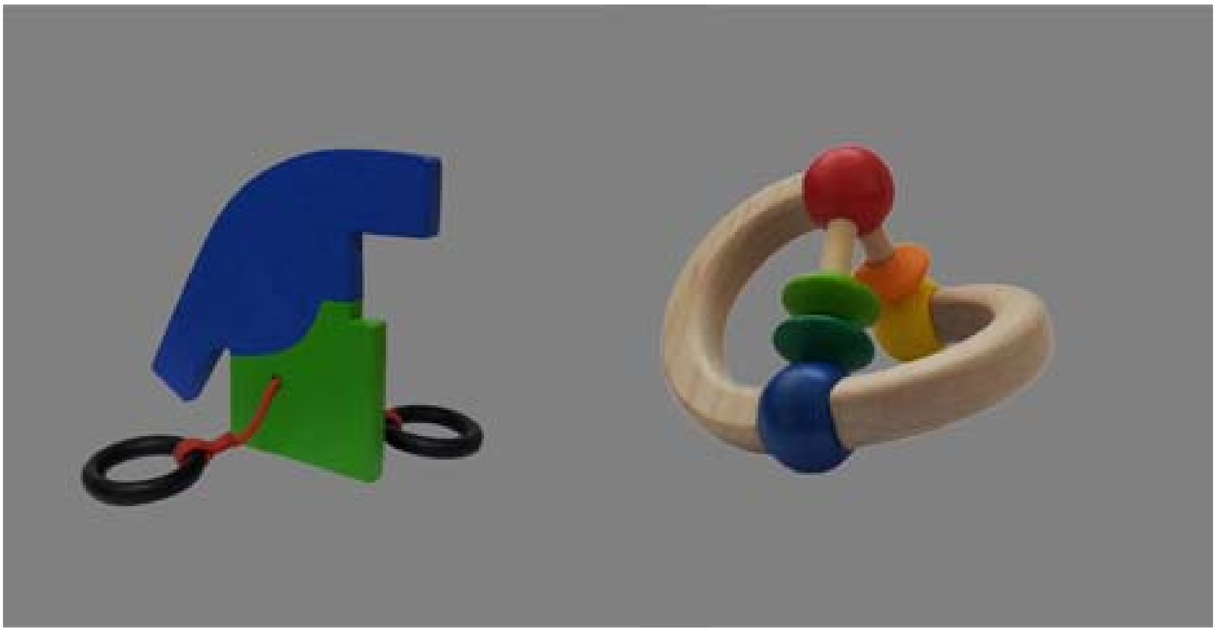

Figure 2.2. Two novel objects used in the experiment

The visual and audio stimuli were presented using custom built routines (PresentMate software developed by Mihaela Duta) in MATLAB (version 7.10.0.499, R2010a, The MathWorks, Inc., Natick, MA) using Psychtoolbox version 3 (Brainard, 1997; Kleiner, Brainard & Pelli, 2007; Pelli, 1997).

Eye tracking

Eye movements were tracked using Tobii TX300 Eye Tracker (Tobii Technology AB, Sweden) with a 120 Hz sampling rate using custom built routines (integrated into the stimuli presentation software above) in MATLAB using the Talk2Tobii Toolbox (Deligianni, Senju, Gergely & Csibra, 2011). The accuracy of the measurement was approximately 0.4° for binocular eye movements.

Data processing and analyses

Three infants were excluded due to poor calibration (for two infants) and experimenter error (one infant). Two infants only completed the first block of testing and training of the experiment due to their fussiness. If less than four training trials were attended, infants were excluded from further analysis (as was the case for one infant). Processing of data was performed in MATLAB (version 8.2.0.701, R2013b). The raw gaze data were smoothed with a 3-point median filter. Fixations were identified automatically using custom routines on the basis of the spatial (within a circle of 35 pixel radius) and temporal characteristics (minimum time for a fixation is 66.7 ms) of the smoothed gaze data. Statistical analysis and visualisation of data were performed using IBM SPSS Statistics 21 (Armonk, NY, USA) and R (version 3.1.0, R-Team, 2008).

As a first step, we plotted the time course (Figure 2.3) of the proportion of infants looking at the target over the course of the test trials after the onset of the label by block of testing. On the basis of this descriptive figure and previous research showing that the maximal response in eye-movements to an auditory label occurs between 1500–2000 ms following the label (Bergelson & Swingley, 2012), one pre-naming time window, and two post-naming time windows (2500-3750 ms and 3751-5000 ms) were chosen for analysis. Using the fixation data obtained from the eye tracker, we calculated the total amount of looking time for the target (T) and distracter (D) for the time windows for each trial. Looking proportion of the target was computed by dividing target looking time by the sum of the target and the distracter looking time (T/(T+D)) within each time window. Trials of the first and the second block of testing were averaged separately. The proportions of target looking of the different time windows were compared by repeated measures ANOVA with time window as a within subject factor and proportion of target looking as the dependent variable.

Results

Data from 34 infants (17 boys, 17 girls) of the initial 38 are reported. Mean age was 14.17 months (SD = 0.27; range 13.73–14.98). Infants were excluded from the ANOVA models if they did not have valid data for at least two trials. This way, the ANOVA for the first block was based on the data of all 34 infants, while 30 infants contributed valid data for the second block. The average number of valid trials was 3.97 (SD = 0.16) for the first and 3.38 (SD = 0.74) for the second block.

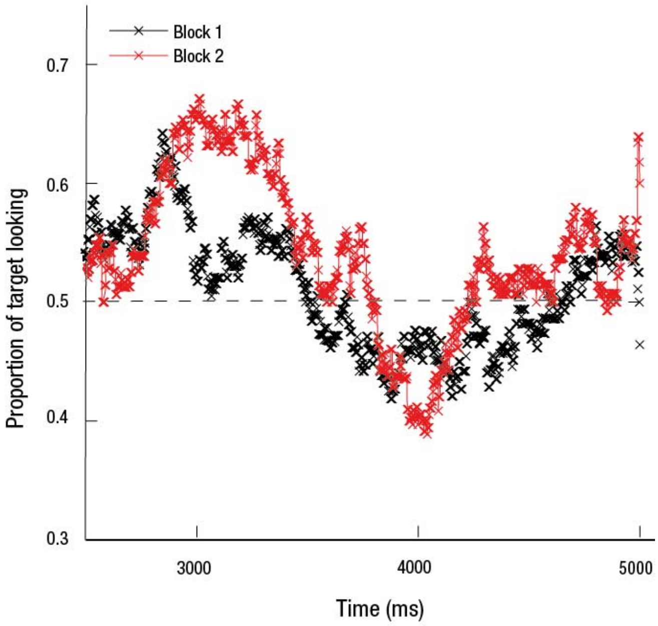

Figure 2.3. Time course analysis in the first and the second testing blocks after the onset of the label. The dashed line at 0.5 indicates chance level.

Figure 2.4 shows the means and standard deviations of the percentage of target looking in three time windows in the first and second blocks. A clear increase in the percentage of target looking can be observed after labelling in the second block. In each block, the proportions of target looking in the different time windows were compared by repeated measures ANOVA with time window as a within subject factor. There was no significant effect of the time window in the first block (F (2, 31) = 1.08; p = .351), indicating that infants did not show signs of learning. However, in the second block, a significant effect of time window was observed (F (2, 27) = 3.45; p = .046, η^2= .20), indicating that the onset of the label caused a change in children's looking toward the named target picture. In particular, pairwise comparisons revealed that the proportion of target looking in the first post-naming window was significantly higher than in the pre-naming time window (p = .018), and in the second post-naming window it was marginally lower than in the first post-naming window (p = .054). Furthermore, the pre-naming time window and the second post-naming time window did not differ significantly (p = .777). Supplementary analyses confirmed that neither sex (block 1: F (2, 28) = 0.94, p = .404, block 2: F (2, 24) = 0.72, p = .498), nor the object-word pairing (block 1: F (2, 28) = 0.31, p = .737, block 2: F (2, 24) = 0.29, p = .75) had a significant main effect or interaction with time window on the proportion of target looking. One sample t-test supported the results, with only the first post-naming window in the second block differing significantly from chance level (see Table 2.1).

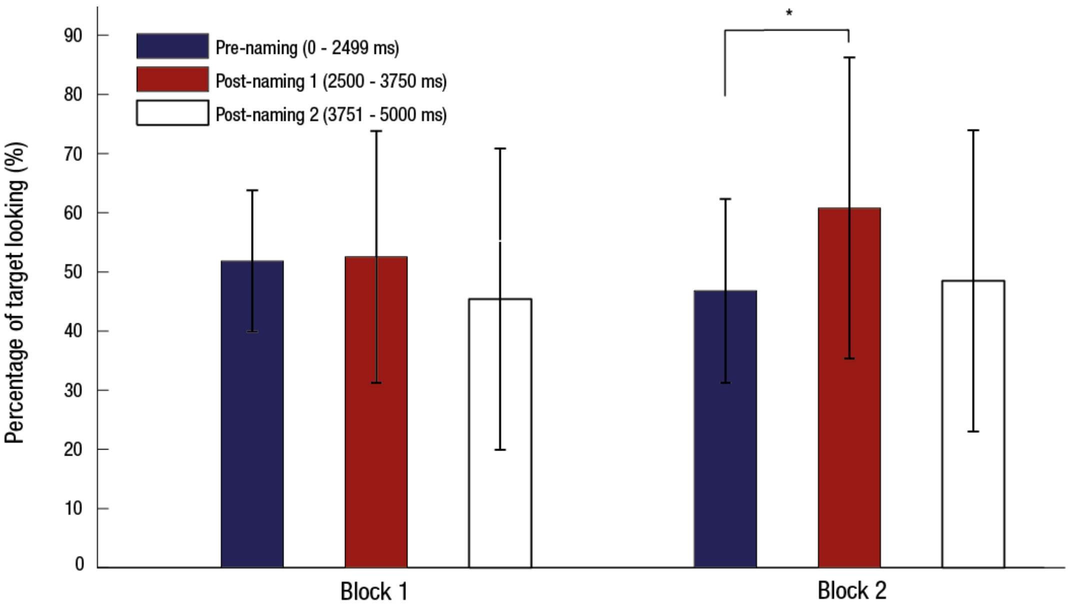

Figure 2.4. Percentage of target looking (means and standard deviations) in three different time windows in the first and the second block. In the second block, infants look more at the target after labelling.

Table 2.1. *Proportion of target looking compared to chance*

		Mean	SD	t	p
Block 1 (df = 32)	Pre-naming	0.52	0.12	0.88	.384
	Post-naming 1	0.53	0.21	0.68	.500
	Post-naming 2	0.45	0.25	-1.04	.308
Block 2 (df = 28)	Pre-naming	0.47	0.16	-1.11	.275
	Post-naming 1	0.61	0.25	2.29	.030
	Post-naming 2	0.49	0.26	-0.32	.751

Notes. df – degrees of freedom, SD – standard deviation

To clarify the early effect of labelling on the time course of target looking, further analyses of the first responsive fixations following the onset of the label were conducted. Figure 2.5 shows the proportion of trials in which infants remained looking at the picture they were fixating on at the time when the label was presented. It is clear that a substantial proportion of children switch their gaze away from the distracter faster than from the target. To investigate this pattern further, we compared the amount of time each child stayed looking at the picture fixated on at the onset of the audio, where it was observed that infants looked away faster in distracter-initial trials than in target-initial trials (M_D = 540.03 ms, SD_D = 624.67 ms vs M_T = 929.18 ms, SD_T = 715.39 ms). For infants who had both target and distracter initiated trials, paired samples t-tests revealed a tendency to look away from the distracter faster (t (8) = 1.88; p = .097); however, our sample size for this comparison was very small (nine infants).

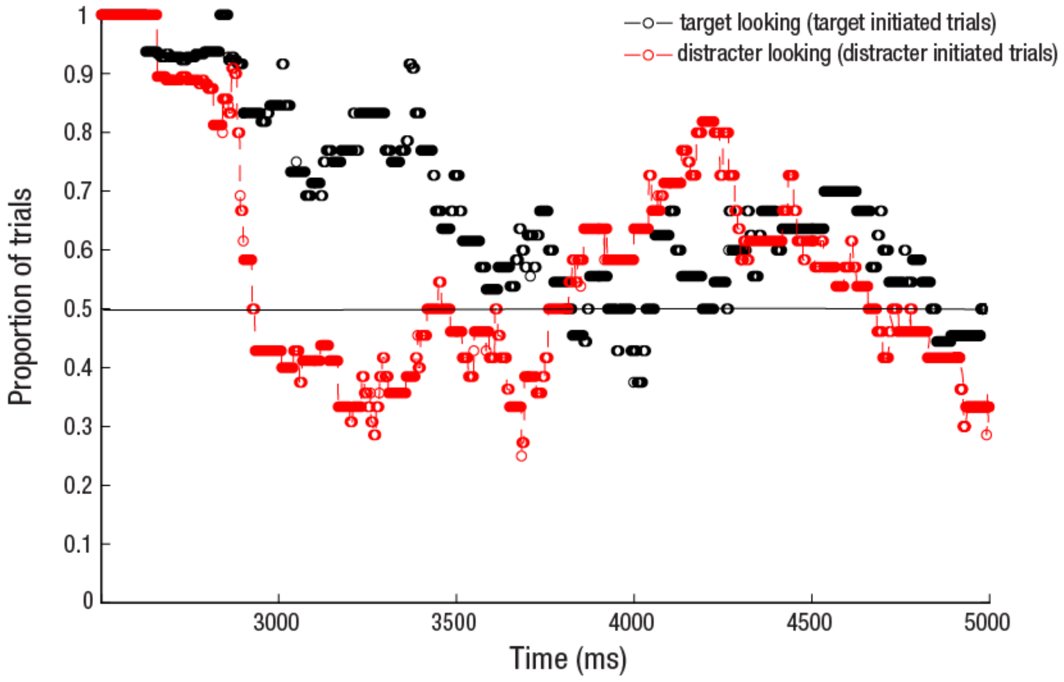

Figure 2.5. Disengagement analysis in the second block. The line at 0.5 indicates chance level.

Preliminary analyses were conducted to investigate whether the time of testing (morning: M = 10:53, SD = 1:03 or afternoon: M = 14:38, SD = 0:59) influences looking behaviour. No significant differences were found between the time of testing or in any measure of target recognition (see Table 2.2). However, there was a tendency in infants tested in the afternoon to show target preference in the first post-naming window of the first block as well (p = .067). To test how these findings are related to the preceding nap or sleep period in infants, we compared the time between the end of the last nap and the beginning of the testing session.

The morning group was significantly closer to the period they spent asleep (t (28) = -2.43, p = .022, morning: M = 52 min, SD = 64 min, afternoon: M = 121 min, SD = 89 min). This suggests that infants in the afternoon group should be more tired, as they spent more time awake. Therefore, it is more likely that it is not tiredness per se, but circadian effects in learning that influenced language acquisition.

Table 2.2. *Comparison of proportion of target looking between morning and afternoon sessions*

		Morning M (SD)	Afternoon M (SD)	t	p
Block 1	Pre-naming	0.51 (0.08)	0.53 (0.16)	-0.52	.606
	Post-naming 1	0.46 (0.19)	0.60 (0.23)	-1.90	.067
	Post-naming 2	0.44 (0.26)	0.48 (0.25)	-0.47	.641
Block 2	Pre-naming	0.47 (0.21)	0.50 (0.11)	-0.44	.661
	Post-naming 1	0.60 (0.27)	0.62 (0.27)	-0.15	.879
	Post-naming 2	0.54 (0.26)	0.43 (0.25)	1.18	.247

Notes. M – mean, SD – standard deviation.

Discussion

Our findings indicate that 14 month old infants are able to learn two new object-label mappings under experimentally controlled conditions. Infants showed learning after 13 repetitions, even though fewer repetitions seemed to be enough in those who were tested in the afternoon. Our results are consistent with earlier studies indicating word learning in infants (Golinkoff et al., 2013; Schafer, 2005; Schafer & Plunkett, 1998; Woodward et al., 1994). We used proportion of target looking as the measure of target preference and confirmed our findings with disengagement analysis. Thus, the paradigm was found to be suitable for further experiments studying the factors which might influence word learning.

However, our results suggested that shorter trial durations may be enough to show target preference in this design. We carried out the analysis in two separate time windows, and target preference occurred in the first; within 1250 ms of labelling. Due to the fact that there were less valid trials in the second block and fewer infants provided valid data, our contention is that shortening trial length may reduce dropouts.

Furthermore, target preference was more pronounced in the second block which may be a consequence of three factors. First, it may indicate that 13 as opposed to 11 repetitions were necessary for learning. Second, a time delay may have been beneficial following training in order for the effect to show, possibly due to offline consolidation. Third, infants might have only understood the task after a few presentations of the testing trials. Interestingly, if data are analysed according to the time of testing (afternoon/morning), infants tested in the afternoon showed learning even in the first block. Comparing the time spent awake between the last period asleep and the beginning of the experiment suggested that it is not the degree of tiredness (the afternoon group spent more time awake) that is behind this finding. Rather, circadian effects may have had an influence. For instance, de Bot (2015), in a study on university students, found that word learning was better in the evening regardless of chronotype, i.e., their individual preference for morning or evening. Further research is needed to clarify the impact of chronotypes and circadian effects on learning in infancy using more sophisticated methods e. g. sleep diaries or actigraphy (a device for measuring rest-activity cycles through measuring acceleration).

Taken together, our research design was shown to be capable of teaching novel words to infants. As a result, it can be concluded that it is suitable for further experiments in combination with napping.

CHAPTER 3. HOW DOES A DAYTIME NAP AFFECT WORD LEARNING IN 16 MONTH OLDS?[*]

This chapter aims to investigate how napping affects word learning in 16 month olds. Thirty four infants were randomly assigned to either nap or wake conditions. After teaching two novel object-word pairs to the infants, their initial performance was tested with an intermodal preferential looking task in which infants are expected to increase their target looking time compared to a distracter after hearing its auditory label. A second test session followed after a delay of approximately 2 hours. The delay contained sleep for the nap group or no sleep for the wake group. Looking behaviour was measured with an automatic eye-tracker and vocabulary size assessed using the Oxford Communicative Development Inventory (OCDI). A significant interaction between group and session was found in preferential looking towards the target picture. The performance of the nap group increased after the nap, whereas that of the wake group did not change. The gain in performance correlated positively with the expressive vocabulary size in the nap group. These results indicate that daytime napping helps the consolidation of novel words in infancy.

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[*] Recruitment and data collection for this study was carried out in collaboration with Kyle Myers, a Final Honours School project student who I supervised.

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Introduction

Infants spend more than half of the day sleeping and napping, yet they acquire new skills easily. One of the skills which develops rapidly during the second year of life is language. In particular, there is a dramatic increase in vocabulary size. In this study, we investigate how daytime napping enhances word learning in 16 month old infants, in order to shed light on the underlying mechanisms of language acquisition and provide insight into the role and importance of napping and sleep.

The enhancing role of sleep in memory consolidation and word learning is well-established in adults and older children. The memory facilitating effects of sleep have been supported in a wide range of paradigms in adults (Diekelmann & Born, 2010; Rasch & Born, 2013), many of them using words as stimuli. Not just consolidation of recognition and recall of newly learnt words are associated with sleep, but also their integration into existing neocortical networks and the mental lexicon (Davis et al., 2009; Dumay & Gaskell, 2007; Tamminen et al., 2010). For children, some studies suggest that a period of offline consolidation is needed to stabilise new phonological representations (Henderson et al., 2012). Brown et al. (2012) found that after familiarising 7 and 12 year old children with novel non-words (e.g. biscal) an improvement in a cued recall task was observed, but only after a 24 hour period. Moreover, Henderson and colleagues (2012) have clarified that not just time but a period of sleep is needed to enhance performance on word recognition and cued recall tasks in 7-12 year olds. Furthermore, stronger enhancement has been found if 5-9 year old children are taught the meanings of the newly learnt word forms (Henderson et al., 2013). Similarly, 6-12 year olds show an improvement in recalling names of cartoon animals after sleep (Ashworth et al., 2014).

Several hypotheses and models can account for these results. The Active System Consolidation Hypothesis, derived from the two-stage model of memory (Marr, 1971), is a widely accepted theory which aims to explain the neurobiological mechanisms underlying the sleep-memory relationship. The main claim of this hypothesis is that during sleep, memory traces are redistributed from short-term hippocampal stores to long-term neocortical store through synchronising slow oscillations, sleep spindles and hippocampal ripples (Diekelmann & Born, 2010). The Active System Consolidation Hypothesis is compatible with the Complementary Learning Systems model (Davis & Gaskell, 2009; McClelland et al., 1995) which also proposes two memory systems, but hypothesises different computational properties for the two systems.

Less is known about the relationship between word learning and sleep in infancy, despite the remarkably longer sleeping times around this age. Total sleep duration decreases from an average of 13.9 hours for one year olds to 8.1 hours for sixteen year olds (Iglowstein et al., 2003). Friedrich et al. (2015) studied word learning and generalisation in 9-16 month old infants by analysing event related potentials. After the learning period, infants acquired word meanings indicated by a late negative component previously associated with word comprehension (Mills et al., 1997). However, after a 1.5 hour gap only those infants who had a nap between the two sessions remembered the word meanings.

In infancy, the impact of sleep on word learning is of importance because word learning plays a key role in accelerating the pace of language acquisition, through developing the mental lexicon, learning phonetic categories and forming the basis for learning the syntactic structure of a language (Swingley, 2009). At least as early as their first birthday, infants are able to associate novel labels with pictures (Houston-Price, Plunkett & Harris, 2005; Pruden et al., 2006; Schafer & Plunkett, 1998). In an event-related potential study, infants as young as six months old were able to learn novel object-label associations (Friedrich & Friederici, 2011). Methodology is crucial in the examination of word learning in infants (Gaskell & Ellis, 2009). For example, many authors claim that learning words is more than just forming associations between objects and labels, since it reflects sensitivity to the social intent of the speaker

(Baldwin, 1991; Tomasello, 1992). Therefore, in our task we included an interactive play session to promote the learning of novel words. One of the most commonly used methods to investigate word learning in infancy is the intermodal preferential looking (IPL) task. In this task infants are predicted to show preferential looking behaviour towards a target compared to a distracter picture after hearing its auditory label if they have learnt the association between object and label (Golinkoff et al., 1987). Furthermore, investigations of word learning are particularly convincing when infants learn two novel words and demonstrate systematic preference for the appropriate referent upon hearing the novel labels when both novel referents are placed side-by-side in competition with each other (Schafer & Plunkett, 1998). We adopt this stringent methodology in the current investigation.

Recently, consolidation of newly learnt words was shown to correlate with expressive vocabulary size (Henderson et al., 2015). Children (7-10 years old) with larger vocabularies demonstrated greater benefits from a 24 hour consolidation period both in terms of lexical integration and explicit phonological memory. This finding converges with earlier results demonstrating that vocabulary size influences performance on different word learning tasks (e.g. Nation, 2014; Wilkinson & Houston-Price, 2013), and implies that novel word consolidation is related to vocabulary size. The authors suggest that new phonological knowledge may be easier to integrate into a rich network. However, there is no data on whether this relationship also exists in infancy or whether the correlation is apparent in a different learning task.

On the basis of the research showing improved memory as a result of a daytime nap or night-time sleep period in adults and children, we hypothesised that infants at the age of 16 months would demonstrate increased target preference after a daytime nap following word learning. Their performance was compared to a wake group. Furthermore, a positive relationship between vocabulary size and the memory-sleep relationship was also hypothesised.

Methodology

Participants

Thirty eight 16 month olds were tested (16 boys). Four infants were excluded from further analysis due to them having had a nap of more than four hours (one), a brief nap between the two sessions in the wake group (one) and language delay (two). All infants were from homes where English was the primary language used. Prior to arrival parents were asked to complete the OCDI (Hamilton, Plunkett & Schafer, 2000) to obtain vocabulary measures, and the Sleep and Naps Oxford Research Inventory (SNORI, see Chapter 5 for more information) to collect data on the infants' sleeping patterns during the preceding week of the appointment. Upon arrival, written informed consent was collected from the caregiver. The study was approved by the University of Oxford Central University Research Ethics Committee (MSD/IDREC/C2/2012/11).

Procedure

Infants were randomly assigned to wake or nap groups during recruitment. The nap group was asked to come in to the laboratory just before their usual nap time, whereas infants in the wake group were brought in at a time when they did not usually nap. In this way, inducing sleep deprivation in the wake group was avoided, and the likelihood of sleeping in the nap group was maximised.

The study design was similar to the one outlined in Chapter 2, although based on our findings (see Chapter 2), trial length was reduced. First, an interactive playing phase took place during which infants were sitting on the caregiver's lap or on the floor. The experimenter introduced two new objects, one at a time. Infants played with and observed the toys with the experimenter labelling each object nine times using carrier sentences—such as: *"Do you want to play with X?", "Where is the X?"*, etc. The order of presentation of the objects and its object-label pairing were counterbalanced across infants and groups. The experimenter was blind to the group membership of the infants, although she was able to infer their group in most of the cases based on the infants' behaviour. Although we do not consider the current experiment to be blind for of the aforementioned reasons, using a predefined script during the interactive play phase minimised the confounding effects.

The play phase was followed by an on-screen training and testing phase. Infants sat on the caregiver's lap approximately 80 cm from the screen and eye-tracker. Before the presentation of the experimental stimuli, a nine-point calibration sequence was conducted for each infant with individual calibration points repeated until four good calibration points were obtained so that the eye-tracker could identify the location of infant visual fixations. The duration of each trial was 3000 ms. Each trial was separated by a 1500 ms animation appearing in the centre of the screen to direct infants' gaze towards the middle. During training, first a block of two familiar word trials (1x dog and 1x book, with the corresponding label) and then a block of four novel word learning (2x *tesh* /tɛʃ/ and 2x *ginn* /gɪn/) trials were presented. The presentation of the trials was randomised within each block. The visual stimulus appeared either on the left or the right side of the screen, the other side was left blank (the side of the novel objects was counterbalanced within infants). The onset of the label was 1500 ms after picture onset, dividing each trial into a pre-naming and post-naming phase of equal duration. The first block of testing trials followed immediately after training; first two familiar objects, then two novel objects were tested. The presentation of the trials within the familiar and the novel block was randomized. The timeline of the two familiar and the two novel testing trials was the same as the training trials, the only difference being that two pictures were presented side-by-side on the screen (see Figure 3.1). The novel objects were tested against each other. The six on-screen training and the four testing trials were immediately repeated once more with the same stimuli. Familiar word learning trials were included to alleviate the repetitiveness of the study and to obtain data about infants' initial engagement in the task on words which they already knew.

After the first train-test session, infants in the nap group had a nap in a specially designated sleep room, whereas infants in the wake group played with their parents in the play area or they went for a walk in town. All infants wore an actiwatch (Mini Actiwatch, CamNtech Ltd, Cambridge, UK) around their ankle in order to confirm that the nap group slept for at least 30 minutes and no more than 3 hours, and that the wake group was awake throughout the 1.5 hour period. Both groups took part in the second testing session where they were presented with a block of two familiar testing trials and a block of two novel testing trials with the same timing as before. Trials within a block were presented in random order. The familiar block always preceded the novel block.

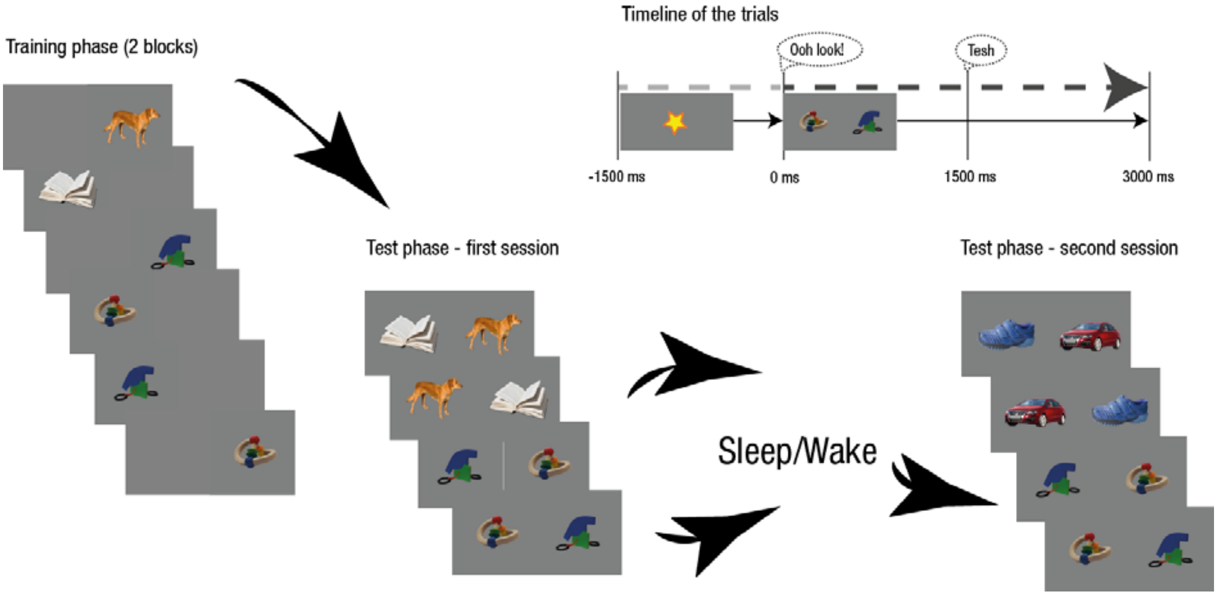

Figure 3.1. Study design and timeline of the trials. There were two blocks of training-testing in the first session and only one in the second session. Trial presentation was randomized within the familiar and the novel block. The familiar blocks were always presented before the novel blocks. The timeline was the same for training and testing with the only difference being the number of pictures presented. After the attention getter animation, objects were presented simultaneously on the screen accompanied by a carrier utterance. At 1500 ms, one of the pictures was labelled.

Stimuli

During the play phase, the same two novel objects were used as in Chapter 2 (see Figure 2.2). The objects were named by the experimenter with the labels (*tesh* /tɛʃ/ and *ginn* /gɪn/). In the on-screen sessions, infants saw colour photographs of the trained objects plus four pictures of four familiar objects (dog, book, shoe and car). The pictures were 1024x768 pixels colour photographs presented on a 50% grey background on a 1920x1080 pixel 58 cm thin film transistor monitor. The distance between the centres of the two pictures was 31 cm.

The pseudowords *tesh* (/tɛʃ/) and *ginn* (/gɪn/) were of 702 ms and 652 ms duration, respectively. The four familiar nouns (*dog, book, shoe* and *car)* were of duration 441 ms, 454 ms, 599 ms and 590 ms, respectively. In addition to the nouns, three attention-getting phrases (*Ooh look!, Hey wow!, Look!*) were also produced by a female native speaker of English in a Southern British accent—as was the case in the initial experimental trial outlined in Chapter 2. Audio stimuli were recorded in a sound-attenuated room with a solid state recorder sampling at 44.1 Hz in 16 bit stereo and were delivered by two speakers centrally located above the screen.

The stimuli were presented using custom built routines in MATLAB (version 7.10.0.499, R2010a, The MathWorks, Inc., Natick, MA) using Psychtoolbox version 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

Eye tracking

Eye movements were tracked using a Tobii TX300 Eye Tracker (Tobii Technology AB, Sweden) with 60 or 120 Hz sampling rates using custom built routines (integrated into the stimuli presentation software above) in MATLAB using the Talk2Tobii Toolbox (Deligianni et al., 2011). The accuracy of the measurement is about 0.4° for binocular eye movements. Data obtained at 120 Hz were downsampled to 60 Hz.

Data Processing and Statistical Analysis

Processing of data was performed in MATLAB (version 8.2.0.701, R2013b). The raw gaze data were smoothed with a 3-point median filter. Fixations were identified automatically using custom routines on the basis of the spatial (within a circle of 35 pixel radius) and temporal characteristics (within 66.7 ms) of the smoothed gaze data. Statistical analysis and visualisation of data were performed using IBM SPSS Statistics 21 (Armonk, NY, USA) and R (version 3.1.0, R-Team, 2008).

Using the fixation data obtained from the automatic eye-tracker, we calculated the total amount of looking time at the target (T) and distracter (D) for both pre- and post-naming phases of each trial. Trials were excluded if looking times in the pre- or in the post-naming phases were zero. Due to trial length, both pre-naming and post-naming was 1000-1000 ms shorter than in Chapter 2—instead of using the proportion of target looking, we define a preference for the target as a difference measure (T-D). To control for object preferences independent of labelling, we calculated a difference measure for the pre-naming phase of the trial (T_{pre}-D_{pre}). We also calculated a similar measure for the post-naming phase of the trial (T_{post}-D_{post}). Each phase of the trial was defined to begin 200 ms after stimulus onset (picture then label), as any saccades launched before this time could not be in response the stimulus (Haith, Hazan & Goodman, 1988). To determine how labelling changes looking behaviour, we define a *naming effect* as the difference between these difference measures, i.e., (T_{post}-D_{post}) - (T_{pre}-D_{pre}).

Results

The data of 31 infants were included in the analysis (wake group: 17; nap group: 14). Three infants were excluded due to failing to acquire data for either one of the sessions. The OCDI data of one infant and the SNORI data of four infants were missing. All infants had regular naps according to the caregiver and confirmed by the SNORI. There was no difference between groups in the OCDI comprehension (t (28) = - 0.87, p = .389) and production scores (t (28) = - 0.90, p = .375), in the time of the day at the start of the experiment (t (29) = 0.12, p = .906) or in the average napping (t (25) = 0.88, p = .387) and sleeping time (t (25) = 0.29, p = .977) during the week prior to testing. However, the two groups differed significantly in age (t (29) = -3.67, p = .001) and in the time difference between the two sessions (t (29) = -2.77, p = .01). Descriptive statistics by group are given in Table 3.1.

Table 3.1. *Descriptive statistics by groups.*

	Wake group	Nap group
	Mean (SD)	
OCDI comprehension	115.88 (64.27)	141.5 (95.13)
OCDI production	17.25 (19.33)	37.79 (88.96)
Time of the day (*hh:mm*)	11:51 (1:59)	11:47 (1:01)
Age (*months*)**	16.09 (0.28)	16.46 (0.28)
Time difference between sessions (*hours*)*	1.79 (0.22)	2.03 (0.26)
Average sleep time (*hours*)	10.86 (0.92)	10.85 (0.82)
Average nap time (*hours*)	2 (0.41)	1.85 (0.46)

Notes. p < .05*, p < .01**, SD – standard deviation.

On the basis of the findings presented in Chapter 2, we compared looking behaviour in the first and second blocks of the first session. Due to the fact that no significant differences were found in either of the groups (wake: t (14) = -0.88, p = .393; nap: t (13) = 1.37, p = 0.195) we averaged the data in the subsequent analyses in order to maximise the number of valid trials.

As the time between the first and the second session can affect forgetting, the infants in the nap group being older and the OCDI score being numerically different between the groups, we included these variables as covariates in a repeated measures analysis of covariance (ANCOVA) model in order to control for possible confounding effects. We did not have OCDI data from one infant, as a result of which we had to exclude him from the analysis. For the novel word learning trials, a significant interaction between group and session (F (1, 25) = 7.98, p = .009, η^2 = .24) was found. No significant main effect of group (F (1, 25) = 0.76, p = .392) or session (F (1, 27) = 0.79, p = .384) emerged. As can be seen in Figure 3.2, there was little change in naming effect apparent for the wake group, whereas the naming effect increased in the nap group. The means (M) and standard deviations (SD) by group are shown in Table 3.2. As a post-hoc analysis, we compared the two groups in the first and the second session with ANCOVA using the same covariates. The groups differed significantly in the second session (F (1, 25) = 4.77, p = .038, η^2 = .16), while there was no difference in the first session (F (1, 25) = 1.57, p = .223). Furthermore, we also analysed the changes within groups with repeated measures ANCOVA using the same covariates. The main effect of session was significant for the nap group (F (1, 10) = 5.31, p = .044, η^2 = .35), but not for the wake group (F (1, 12) = 0.17, p = .689). As a post-hoc analysis, we investigated with one sample t-tests whether the raw values of the naming effect were significantly different from zero. Interestingly, in the second session neither of the groups differed significantly from zero (nap: t (13) = 1.21, p = .250, wake: t (15) = -0.98, p = .343). However, in the first session while the wake group was not significantly different from zero (t (15) = -0.041, p = .968), the nap group was (t (13) = -3.18, p = .007). In the case of the nap group, a negative naming effect was apparent.

Table 3.2. *Group differences in the naming effect*

	Novel word trials		Familiar word trials	
	Wake group	Nap group	Wake group	Nap group
	Mean (SD) in ms		Mean (SD) in ms	
Session 1	-7.65 (741.4)	-292.76 (344)*	400.46 (160.8)**	464.02 (118.3)**
Session 2	-174.5 (712.2)	270.25 (839.47)	454.08 (318.32)**	434.47 (319.95)**

Notes. One sample t-test results: p < .01*, p < .001**, SD – standard deviation.

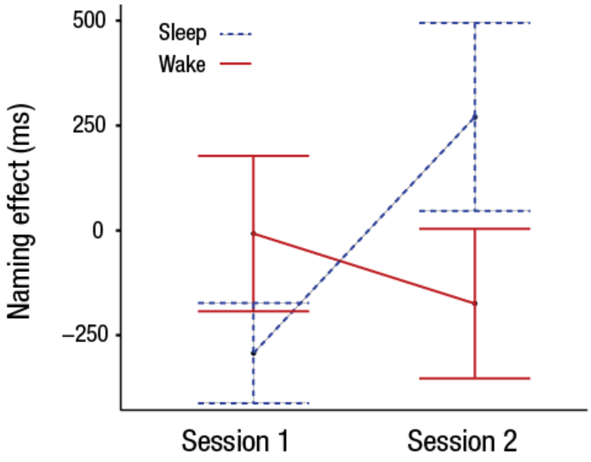

Figure 3.2. Group–session interaction on the novel word learning trials. After sleeping, the target preference of the nap group increases. Means and standard errors are presented.

We also analysed the naming effect for the familiar trials in the first session to study whether the group difference in the novel word learning trials reflects dissimilar initial engagement in the task. It is important to note that fewer infants provided valid familiar word data from the second session; therefore participant numbers in the groups vary. Independent sample t-tests did not reveal significant differences between groups in either of the first (t (30) = -1.27, p = .213) or the second session (t (25) = 0.16, p = .875). One sampled t-tests were performed to examine whether the naming effect differed significantly from zero. Both groups showed a significant positive naming effect in both the first (wake: t (15) = 9.96, p < .001; nap: t (15) = 15.69, p < .001) and the second session (wake: t (11) = 4.94, p < .001, nap: t (14) = 5.31, p < .001). Means and SDs are presented in Table 3.2. These results confirm that both groups were sensitive to the task demands and increased their target preference after labelling. Moreover, they also suggest that in the two sessions both groups had similar level of alertness.

To determine whether vocabulary size is associated with the change in performance on novel words (the difference between the naming effects in the first and second sessions), we performed a correlation analysis by group. One data point was removed because it was considered as an outlier (over 1.5x the inter-quartile range). For the nap group, only the OCDI production score (r (13) = .67, p = .013, see Figure 3.3) correlated significantly with the performance change (OCDI comprehension score: r (13) = .32, p = .294). For the wake group no such association was found with either the OCDI production (r (16) = - .05, p = .859) or comprehension score (r (16) = - .34, p = .198). To investigate whether the correlation is specific to expressive vocabulary, we calculated a partial correlation in the nap group with comprehension score as the controlled variable. The correlation remained significant (r (10) = .50, p = .03). The results indicate that infants with a larger productive vocabulary score benefit more from a nap after learning.

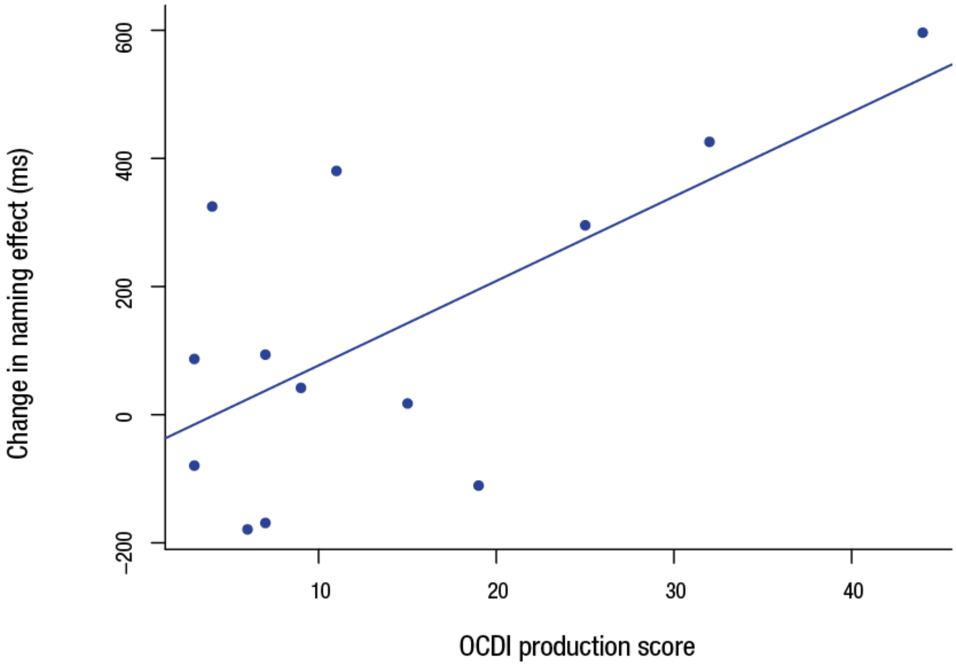

Figure 3.3. Correlation (r (13) = .67, p = .013) between the OCDI production score and the performance gain in the nap group.

Discussion

This study demonstrates the beneficial effect of a nap on word learning, as measured with behavioural methods, in infancy. After training on two novel word-object associations, both the nap and the wake group were tested on initial performance. The groups did not differ in performance either in novel or familiar word trials, both groups responding appropriately to familiar words indicating that they were on task. A second testing session, conducted after approximately a two hour delay, contained a period of sleep for the nap group. The nap group showed significantly increased target looking time after a daytime nap in the laboratory, while there was no systematic change in looking behaviour in the wake group in the novel word trials. Furthermore, both groups showed a positive naming effect in the familiar word trials, suggesting they had similar level of alertness in the second session. This outcome indicates sleep dependent consolidation of newly learnt word forms in association to novel objects.

Our results are consistent with the current literature describing the relationship between sleep and memory in adults (Rasch & Born, 2013), children (Rasch & Born, 2013) and infants (Friedrich et al., 2015). As the performance of the wake group did not change between the two sessions, it is improbable that the group difference was a result of forgetting. The increase in the sleep group suggests enhanced memory for words after napping. Our findings are similar to those of Henderson and colleagues (2012) who found a facilitative role of sleep in recalling words in 7-12 year old children, while sleep seemed to play a consolidating role in a non-verbal memory task.

However, comparing the naming effect by group and by session to zero did not result in significant differences, except for the negative naming effect in the first session in the sleep group. The lack of significant results may be a consequence of the high variability in looking times observed in infants, indicated by the large standard deviations. The negative naming effect is a preference for the distracter, which is hard to interpret. It is unlikely that the infants mapped the wrong labels to the objects, because after napping, they showed a numerically positive naming effect. The results might reflect a novelty preference for the mismatch between the label and the object. Further, for the wake group, a numerically negative although not significant naming effect was found. We speculate that tiredness may be related to these findings, perhaps due to oversaturation of the neural networks involved in learning the new object-label mappings. After consolidation of the new words during sleep, different neural structures are activated (Davis et al., 2009) and this can lead to the positive naming effect. This claim is also supported by the positive naming effect and the lack of group differences found in the familiar trials in response to words which had been previously consolidated. It is important to emphasise that because of the high variability in the data and the lack of significant results, our conclusions are more tentative in nature. Importantly, the change in performance after sleep may have been driven at least partly by the negative naming effect in the first session. Further investigations are warranted to disentangle the relationship between tiredness, word consolidation and the negative naming effect.

We also find a positive association between expressive vocabulary size and performance gain in the nap group similarly to a study carried out in children by Henderson et al. (2015). One possible explanation for this result is that consolidation is more efficient if there are more representations in the long-term neocortical network (Tse et al., 2007; Wilhelm, Prehn-Kristensen, et al., 2012), although it would not elucidate why this association was not observable for receptive vocabulary. A more plausible explanation would be that, similarly to animal models, sleep plays a role in the fine tuning of the pre-motor and motor representations with greater efficiency if representations are already present (Wilhelm, Prehn-Kristensen, et al., 2012). In zebra finches, the consolidation of a tutored song was facilitated by sleep in adults, whereas in juvenile birds, their performance deteriorated after sleeping (Shank & Margoliash, 2009). Facilitation was associated with replay activity during sleep in the pre-motor and motor structures of the bird's vocal control system. In juvenile birds, however; the replay activity showed a decline across sleep (Day, Kinnischtzke, Adam & Nick, 2009). Importantly, the substantially degraded performance of surgically muted birds suggests that the replay is controlled by the auditory feedback from the bird's own singing. These results suggest that in juvenile birds there is a significant difference in the representation of the tutored song and the auditory feedback (the bird's own singing) that leads to less established sensorimotor integration (Margoliash & Schmidt, 2010). We might speculate that there is an analogy to human infants. Infants whose expressive vocabulary was lower did not benefit as much from sleep because they were less able to integrate sensorimotor representations. The reduced capacity for sensorimotor integration might be the result of fewer existing representations (Tse et al., 2007; Wilhelm, Prehn-Kristensen, et al., 2012) or less developed oral motor control which was shown to be associated with language production (Alcock & Krawczyk, 2010).

On the other hand, we did not find a significant correlation between vocabulary size and performance gain in the wake group. This, together with the significant positive correlation in the sleep group, suggests that vocabulary size directly influences sleep-dependent memory consolidation. The active system consolidation hypothesis postulates that during sleep memory traces are redistributed from short-term hippocampal stores to long-term neocortical stores through synchronising slow oscillations, sleep spindles and hippocampal ripples (Diekelmann & Born, 2010). Because the representations of words (thus vocabulary size) are related to long-term neocortical stores, the number of representations can only have an effect if the neocortex is involved in the memory processes. In this way, the lack of correlation suggests that the wake group failed to consolidate the novel words because the hippocampo-neocortical transfer did not happen. Most probably, circadian effects did not influence our results as there was no difference in the timing of the testing between the groups. One could argue that the two groups' apparently disparate looking behaviour on the novel word trials is a consequence of different levels of engagement in the task. However, the lack of any systematic differences in target preferences in the familiar word trials during the two testing sessions points to task engagement in both groups. Moreover, both groups increased their target looking times after labelling, indicating that they understood the task. A possible limitation of this investigation is the age difference between the nap and wake groups. The nap group was 11 days older on average than the wake group. This difference was handled analytically by including age as a covariate in the statistical models.

Based on the results of the current experiment, it remains undetermined whether sleep plays an active role in consolidation or whether sleep renders consolidation more efficient due to sleep preventing the encoding of interfering information in the 16 month old infants. Nor can we make inferences about the length of the retention period for word-object associations. It is possible that the wake group would show improvement in memory after a subsequent period asleep, similarly to that reported by Henderson et al. (2012) (though, see Kurdziel et al. (2013)). Further studies are needed to clarify this question given the important practical consequence for social policies promoting napping.

To conclude, our findings emphasise the importance of sleep and napping in consolidating newly formed object-label associations by 16 months olds. The consolidation of object-label mapping is crucial in word learning and overall language development. Considering that around this age, infants go through an intensive period of vocabulary development, promoting healthy sleep-nap patterns—especially in this age group—should be of the utmost importance.

CHAPTER 4. HOW DOES A DAYTIME NAP FACILITATE GENERALISATION OF WORD MEANINGS IN 16 MONTH OLDS?*

One of the key processes in language development is generalisation—the selection and extension of relevant features and information to similar objects and concepts. Little is known about how sleep influences generalisation in infancy and studies on the topic are inconclusive (Friedrich et al., 2015; Gomez et al., 2006; Werchan & Gomez, 2014). Our aim was to investigate how a nap affects generalisation in 16 month olds. We hypothesised that a nap is necessary for successful generalisation of word meanings. We trained 28 infants with two novel object-word pairs and tested their initial ability to generalise. Infants took part in an intermodal preferential looking task, in which they were shown different coloured versions of the original objects and heard one of the trained labels. If infants understand the label, they are expected to increase their looking time to the target. Infants were randomly assigned to nap or wake groups. Afterward, the nap group went to sleep, while the wake group stayed awake for approximately two hours. We then repeated the test of their performance on the generalisation task. Looking behaviour was measured with an automated eye tracker. A significant interaction of group and session was found in preferential looking. The performance of the nap group increased after the nap, whereas that of the wake group did not change. Our results suggest that nap improves generalisation in infants.

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* Recruitment and data collection for this study was carried out in collaboration with Siying Liu, an MSc project student who I supervised.

Parts of this chapter have been submitted and accepted as:
Horvath, K., Liu, S., Plunkett, K. (2016). A daytime nap facilitates generalization of word meanings in young toddlers. Sleep, 39(1), 203-207.

Introduction

Generalisation of word meanings to similar objects is a key process in acquiring knowledge about the environment, because it saves the cognitive effort of learning the names of objects individually. The underlying mechanisms involve consolidation processes that can take place either online (i.e. at the same time as the encoding) or offline (after encoding). A great body of literature suggests that in adults sleep facilitates generalisation offline (Ellenbogen et al., 2007; Fenn et al., 2003; Gaskell et al., 2014; Lau, Alger & Fishbein, 2011; Stickgold & Walker, 2013; Wagner et al., 2004); however, the picture is less clear regarding infants who are in the most intensive stage of learning word meanings.

Generalisation makes it possible to adapt previously gained knowledge to new situations on the basis of identified similarities. To be able to recognize the crucial commonalities an abstract representation is required (Son, Smith & Goldstone, 2008). Sleep may play a role in selecting the relevant features that should be represented and in promoting the forgetting of irrelevant information; thus, reorganising memory (Friedrich et al., 2015). Several studies showed that after sleep, adults are more efficient in tasks that require generalisation, e.g., synthetic speech recognition (Fenn et al., 2003), finding a hidden rule in a mathematical problem (Wagner et al., 2004), or a relational memory task (Ellenbogen et al., 2007; Lau et al., 2011).

Recently, similar claims for the role of sleep in the generalisation of word meanings in 9 to 16 month olds have been reported (Friedrich et al., 2015). Friedrich and colleagues, using event-related potentials, showed that during an initial training period infants were capable of learning specific word meanings but were not able to learn names for categories consisting of similar pictures. However, after a 1.5 hour nap infants (without further training) could generalise the category names for novel exemplars and could also remembered the specific word meanings. In contrast, the wake group seemed to forget the specific word meanings and did not show generalisation. Moreover, the generalisation effect was associated to a specific sleep EEG oscillation, i.e. sleep spindles.

The opposite effect has been reported by Werchan and Gomez (2014), who found that a period of wake, not sleep, facilitates generalisation of word meanings. Toddlers aged 2.5 years learned a label for a category consisting of three exemplar objects. The toddlers were also familiarized with a distracter (without labelling). Four hours later they were presented with four objects: a novel exemplar of the learned category, the distracter and two novel objects, and were asked to point to the target image using the label of the category. The performance of children who had a nap between the two sessions was significantly worse than those who remained awake.

To clarify the role of sleep in generalisation of word meanings in infancy, we adapted the methodology we used in Chapter 3, in which we demonstrated that a nap facilitates the consolidation of novel object-word associations. The IPL paradigm with automatic eye tracking makes it possible to obtain data on the behavioural level while relying less on the infant's active participation. In the current study, we hypothesised that 16 month old infants would only be able to generalise novel object-word associations to object exemplars beyond the original training set after they had a nap.

Methodology

Participants

Data from 28 infants were analysed (nap group: 14, wake group: 14, male: 16, female: 12). Nine additional infants were tested but excluded from further analysis due to non-completion of the task (due to crying, refusing to participate) or insufficient eye-tracking data—five and four infants, respectively. Of the nine infants excluded, four were in the wake group. All infants were from families in which English was the primary language used and they were all Caucasian. On average, the infants' mothers spent 17.07 years in education. Parents were asked to complete the OCDI (Hamilton et al., 2000) to obtain vocabulary measures prior to arrival, as well as the SNORI to collect data on the infants' sleeping patterns during the week preceding the appointment. If the parents did not fill in the SNORI (nine infants), they were asked whether their infant had regular naps and whether there had been anything unusual in their child's sleeping pattern in the previous three days. Written informed consent was collected from the caregiver. The study was approved by the University of Oxford Central University Research Ethics Committee (MSD/IDREC/C2/2012/11).

Stimuli

During the play phase, four novel objects (see Figure 4.1) were used. Two objects (original objects) were named by the experimenter with the labels *tesh (/*tɛʃ/) and *ginn* *(/*gɪn/). The other two objects served as generalisation objects and differed in colour, but not in shape or texture, from the original objects. In the on-screen sessions, infants saw colour photographs of the trained original objects plus eight extra pictures (dog, cow, cat, duck, ball, book, cup and shoe) as familiar stimuli. The pictures were 1024x768 pixels colour photographs presented on a 50% grey background on a 1920x1080 pixel, 58 cm thin film transistor monitor.

The audio stimuli consisted of the aforementioned pseudowords (*tesh* /teʃ/ and *ginn* /gɪn/, duration: 702 ms and 652 ms, respectively), eight familiar nouns (*dog, cow, cat, duck, ball, book, cup and shoe*) and two attention phrases (*Ooh look!, Hey wow!*) produced by a female native speaker of British English in a Southern accent. Audio stimuli were recorded in a sound-attenuating room with a solid state recorder sampling at 44.1 Hz in 16 bit stereo and were delivered by two speakers centrally located above the screen.

The stimuli were presented using custom-built routines in MATLAB (version 7.10.0.499, R2010a, The MathWorks, Inc., Natick, MA, USA) using Psychtoolbox version 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

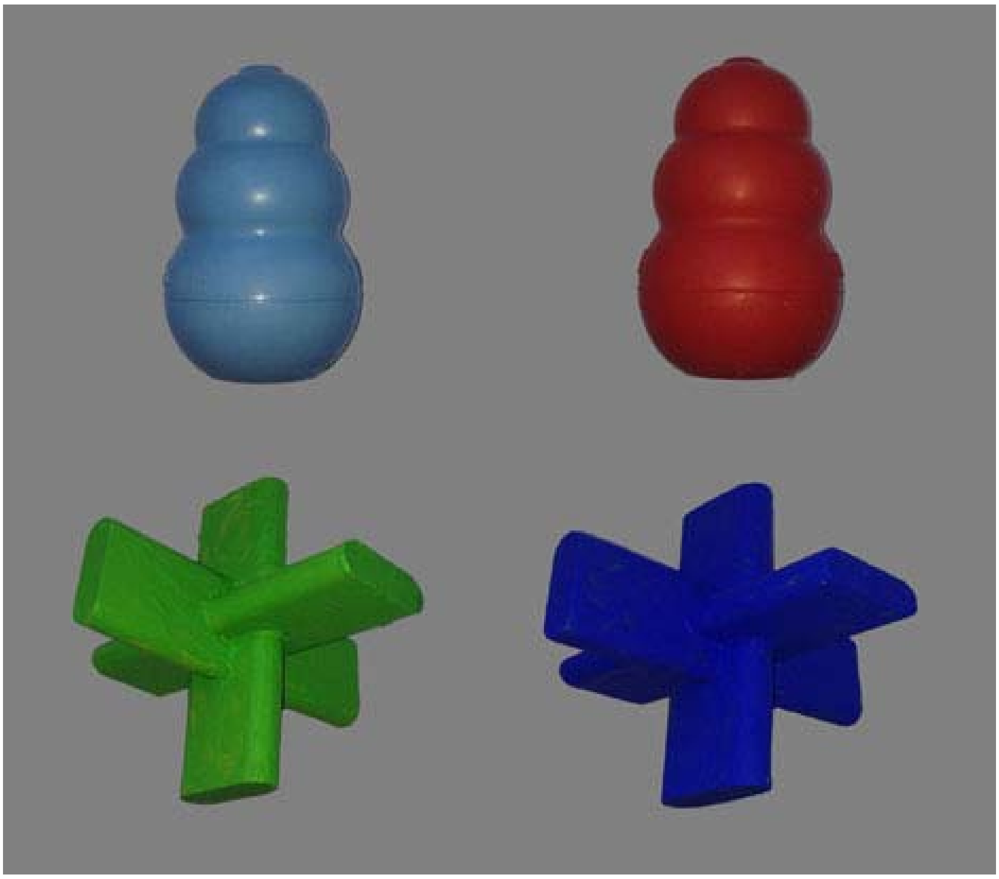


Figure 4.1. The four novel objects used in the experiment.

Eye Tracking

Eye movements were tracked using a Tobii TX300 Eye Tracker (Tobii Technology AB, Sweden) with 120 Hz sampling rate with custom built routines (integrated in the stimuli presentation software above) in MATLAB using the Talk2Tobii Toolbox (Deligianni et al., 2011). The accuracy of the measurement is about 0.4° for binocular eye movements.

Procedure

The procedure was an adaptation of that used in Chapter 3. Infants were randomly assigned to wake or nap groups during recruitment. To avoid causing sleep deprivation in the wake group, the testing of the wake group was scheduled at a time when the infants did not usually nap. To maximise the chance for a daytime sleep, the nap group was brought into the laboratory just before their usual nap time.

First, an interactive playing phase was conducted while infants sat on the floor, sofa, or the caregiver's lap. The experimenter introduced the two new original objects, one at a time. Infants played with and observed the toys, while the experimenter labelled each one six times using carrier sentences such as: "*Show mummy/daddy the X!" "Where is the X?"* The order of the presentation of the objects and the object-label pairing were counterbalanced across participants and groups. Afterward, infants were familiarised with the two generalisation objects that had the same shape as the novel objects, but differed in colour. The same carrier sentences were used but the label was replaced by a pronoun (it/this).

Then, an on-screen training and testing phase took place. Infants sat on the caregiver's lap approximately 80 cm from the screen and the eye tracker. Before the presentation of the experimental stimuli, a nine-point calibration was conducted with individual calibration points repeated until four good calibration points were obtained so that the eye tracker could identify the location of visual fixations. Each trial was 3000 ms long, and was preceded by a 1500 ms long animation appearing in the middle of the screen to direct infants' gaze toward the centre. The onset of the audio label occurred 1500 ms after the onset of the test objects. The timeline of an example generalisation testing trial is shown in Figure 4.2.

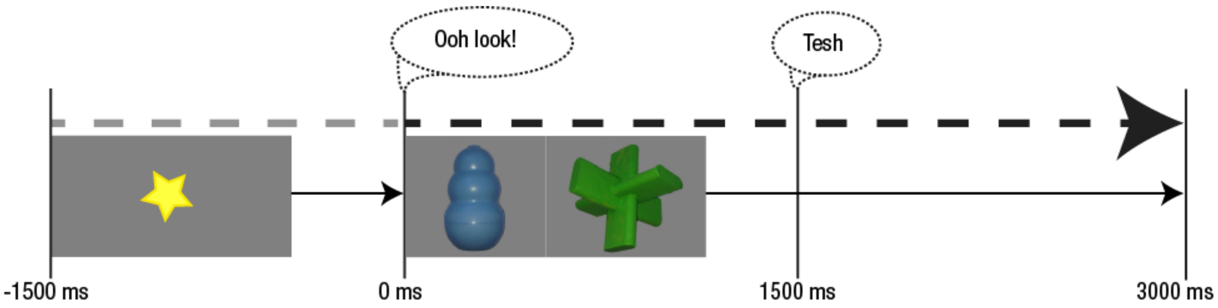


Figure 4.2. The timeline of the trials. Here, we show a testing trial for the generalisation objects.

First, a block of four familiar testing trials was presented where pictures of two familiar objects were shown side by side (e.g., cat and duck) and one of them was labelled. We included these trials to provide infants with some time to understand the task. Then, a block of six novel object training trials were shown and named with its associated auditory label, one at a time either on the left or the right side of the screen (counterbalanced within infants). This was followed by a block of four novel object testing trials, with the pictures of the two novel objects presented simultaneously, side-by-side. After which, to familiarise infants with the generalisation objects on screen, we presented four generalisation object trials where a picture of one of the generalisation objects was shown, accompanied with an attention-getter sentence (without a label). Each generalisation object was presented twice, once on each side of the screen. Finally, both generalisation objects were presented side-by-side four times and one of the labels of the original objects was spoken. The side of the labelled generalisation object was counterbalanced within infants. The order of the trials within a block was randomised.

The second testing session was approximately 1.5 hours after the first. During this period, infants in the nap group had a daytime nap in the laboratory, whereas infants in the wake group played with their parents in the play area or they went for a walk in town. Infants wore an actiwatch (Mini Actiwatch, CamNtech Ltd, Cambridge, UK) around their ankle in order to ensure the nap group slept and that the wake group remained awake. Infants could nap as long as they wanted (M = 59 min, SD = 29.69). The second testing session consisted of a block of four familiar object testing trials, a block of four generalisation testing trials and a block of four novel object testing trials in random order within block.

Data Processing and Statistical Analysis

Processing of data was performed in MATLAB (version 8.2.0.701, R2013b). The raw gaze data were smoothed with a three-point median filter. Fixations were identified automatically using custom routines on the basis of the spatial (within a circle with 35 pixel radius) and temporal characteristics (within 66.7 ms) of the smoothed gaze data. Statistical analysis and visualization of data were performed using IBM SPSS Statistics 22 (Armonk, NY, USA) and R (version 3.1.2, R-Team, 2008).

Using the fixation data obtained from the automatic eye tracker, we calculated the total amount of looking time at the target (T) and distracter (D) for both pre-naming and post-naming phases of each trial as we did in Chapter 3. We define a preference for the target as a difference measure (T-D). To control for object preferences independent of labelling, we calculated a difference measure for the pre-naming phase of the trial (T_{pre}-D_{pre}). We also calculated a similar measure for the post-naming phase of the trial (T_{post}-D_{post}). Each phase of the trial was defined to begin 200 ms after stimulus onset (picture, then label), because any saccades launched before this time could not be in response to the stimulus (Haith et al., 1988). To determine how labelling changes looking behaviour, we define a naming effect as the difference between these difference measures, i.e., (T_{post}-D_{post}) - (T_{pre}-D_{pre}).

Results

The data of 28 infants were analysed. All infants had regular naps according to the caregiver and confirmed by the SNORI or by interview. There was no significant difference between the groups in OCDI score, age, time difference between the sessions, time of day of the training and testing, maternal education, sleep time and nap time. Descriptive and t-test statistics are presented in Table 4.1.

Table 4.1. *Descriptive statistics.*

	Wake M (SD)	Nap M (SD)	t (df)	p
OCDI comprehension	162.43 (133.33)	122.64 (93.06)	- 0.92 (26)	.368
OCDI production	36.79 (90.14)	17.79 (24.76)	- 0.76 (26)	.454
Age (*month*)	16.25 (0.83)	15.40 (2.87)	- 1.06 (26)	.299
Time difference between sessions (*min*)	110.07 (22.54)	125.07 (32.41)	1.42 (26)	.167
Time of the day at the training session (*hh:min*)	11:53 (1:55)	12:32 (1:20)	1.02 (26)	.320
Time of the day at the testing session (*hh:min*)	13:43 (1:55)	14:37 (1:21)	1.42 (26)	.168
Maternal education (*years* spent in education)	17.00 (1.95)	17.14 (2.73)	0.16 (26)	.874
Average sleep time (*min*)	645.69 (54.2)	647.72 (61.24)	0.08 (17)	.935
Average nap time (*min*)	118.75 (25.28)	102.76 (38.9)	-1.07 (17)	.298

Notes. M – mean, SD – standard deviation, df – degrees of freedom.

To determine whether the two groups changed in generalisation performance over the 1.5 hour period, including sleeping for the nap group, we used a repeated-measures analysis of covariance. Age, CDI score and the time difference between the two sessions were included as covariates because they may influence test performance. There was no significant main effect of session (F (1, 23) = 0.02, p = .882), but a significant interaction emerged between session and group (F (1, 23) = 1.81, p = .049, η^2= .19). The interaction is shown in Figure 4.3. Follow-up comparisons revealed that the naming effect in the nap group increased (t (13) = -2.93, p = .012, Cohen d = -.78), whereas there was no change in the wake group (t (13) = 0.10, p = .924). One sample t-tests indicated that only the nap group showed learning (i.e., naming effect was significantly different from zero) and exclusively in session two. Descriptive and t-test statistics are shown in Table 4.2. There was no correlation between sleep time and change in performance in the nap group.

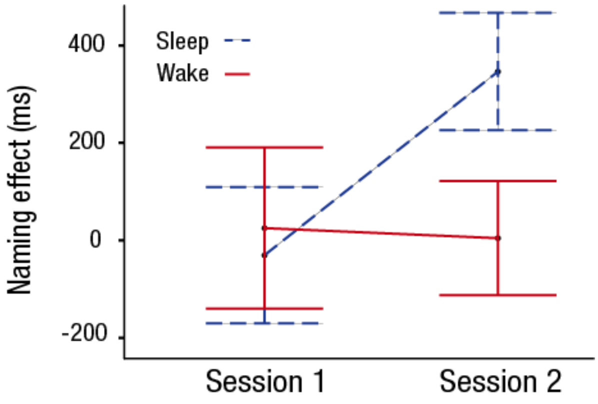


Figure 4.3. Change in naming effect between sessions by group. A significant interaction between session and group emerged. Means and standard errors are presented.

Table 4.2. *The naming effect in the generalisation trials by session and group. Figures are displayed in milliseconds.*

		M	SD	*t*	p
Session 1	Nap	-30.41	522.57	-0.22	.831
	Wake	25.15	619.47	0.15	.882
Session 2	Nap	346.46	450.84	2.88	.013
	Wake	4.49	438.91	0.04	.970

Notes. M = mean; SD = standard deviation.

To rule out the possibility that infants' levels of attention were different in the two groups, we compared the mean total looking time of the trials in the nap and the wake group with independent sample t-tests. No significant difference emerged in either session 1 (t (26) = -0.78, p = .440, mean difference: -73.06 [-264.71 118.59], SE: 93.24), or session 2 (t (26) = -0.26, p = .799, mean difference: -25.72 [-231.52 180.08], SE: 100.12).

Furthermore, we also analysed the familiar object trials to confirm that both groups were on task and that they did not differ systematically. We conducted a repeated-measures analysis of covariance with the same covariates as for the generalisation objects. There was neither a significant main effect of session (F (1, 23) = 0.35, p = .560), nor an interaction between session and group (F (1, 23) = 0.01, p = .945). One-sample t-tests were also performed to see whether both groups participated in the task. Means and t-statistics can be found in Table 4.3. Both groups showed a significant naming effect, but only in the first session. An independent sample t-test confirmed that the two groups did not differ (session 1: t (26) = 0.843, p = .407, session 2: t (26) = 1.066, p = .296).

Table 4.3. *The naming effect in the familiar trials by session and group. Figures are displayed in milliseconds.*

		M	SD	*t*	p
Session 1	Nap	523.5	507.97	3.856	.002
	Wake	357.93	531.58	2.519	.026
Session 2	Nap	148.15	555.49	0.998	.337
	Wake	-34.25	317.74	-0.403	.693

Notes. M = mean; SD = standard deviation.

Similarly, we compared the performance of the two groups on the novel word trials with a repeated-measures analysis of covariance with the same covariates as before. There was no significant main effect of group (F (1, 23) = 0.22, p = .647) or session (F (1, 23) = 0.39, p = .537), and no interaction between group and session (F (1, 23) = 0.24, p = .630). One sample t-tests did not indicate word learning for novel trials in either sessions or groups.

Finally, we tested whether OCDI score correlated with the improvement in performance for the generalisation trials—as with our experiment described in Chapter 3. No significant correlations were found either with comprehension score (nap: r (14) = .15, p = .615; wake: r

(14) = 0.04, p = .901), or production score (nap: r (14) = -.36, p = .203; wake: r (14) = .07, p = .811).

Table 4.4. *The naming effect in the novel word trials by session and group. Figures are displayed in milliseconds.*

		M	SD	*t*	p
Session 1	Nap	53.94	386.3	0.523	.61
	Wake	-33.36	318.97	-0.391	.702
Session 2	Nap	38.68	349.77	0.414	.686
	Wake	39.8	247.49	0.602	.558

Notes. M = mean; SD = standard deviation.

Discussion

This study provides additional evidence that sleep facilitates generalisation of word meanings in infants and thereby reinforces the results of Friedrich et al. (2015) with a method different from electrophysiology, the method previously used. In this study, we used automatic eye tracking in the IPL paradigm to investigate whether infants were able to generalise novel words to objects of similar kind. Infants were trained with two object-word pairs and tested with objects that had different colours but the same shape. Infants were not able to generalise the name of the object immediately after training. However, the sleep group generalised successfully after having a nap in the laboratory. Although Friedrich et al. (2015) trained with eight objects per category, in this study infants were shown only one exemplar of a category, which was enough for generalising the word meaning.

The facilitating effect of sleep on generalisation in infancy was first shown by Gomez et al. (2006). Infants were presented with word strings with an underlying rule where the first word predicted the third. After a nap, infants were able to generalise this rule to stimuli that were previously not heard. This effect was observable after 24 hours, but only in the nap group

(Hupbach et al., 2009). The studies of Friedrich and colleagues, and the current study, extend this grammar-related observation to the acquisition of word meanings.

However, it has been observed elsewhere that wake, and not sleep, promotes the generalisation of word meanings (Werchan & Gomez, 2014). It is important to note that in their study, Werchan and Gomez tested an older age group (2.5 year olds), suggesting that the role of sleep in generalisation might change during development (Gomez & Edgin, 2015). However, there are many studies in adults that show sleep dependent generalisation (Ellenbogen et al., 2007; Fenn et al., 2003; Gaskell et al., 2014; Stickgold & Walker, 2013; Wagner et al., 2004). Thus, it is possible that other factors contributed to the contrasting pattern of results. Friedrich et al. (2015) suggest that contextual changes such as the change in background colour and texture may account for different findings. Furthermore, Werchan and Gomez's task required pointing, which means that other factors influencing infants' levels of cooperation might affect the results. In addition, circadian effects cannot be ruled out as there was an almost a 2 hour difference—approaching statistical significance—in the time of day at testing and at learning.

Circadian effects might also have an effect on our results. Although there was no time difference in the time of the day at training or testing, infants in the nap group were brought into the laboratory before their usual nap time and infants in the wake group arrived after their usual nap. This might mean that they were in a different phase in their circadian cycle. However, we found no difference between the groups in total looking time, indicating similar levels of attention to the task. It is still possible that we did not see an improvement in performance in the wake group because of their increased tiredness.

Another limitation of our study is that neither of the groups seemed to be on task in the familiar trials in the second session. This might have resulted from repeating the same familiar trials as those in the first session. Furthermore, as these trials were at the beginning of the testing session, sleep infants may have still been drowsy because they had just woken up, and wake infants would have required longer time to focus on the task as they were tired. Having said that, the lack of any systematic differences between groups in the familiar trials suggests that the differences in performance in the generalisation trials were not a consequence of different levels of participation in the task.

Furthermore, the lack of sleep dependent consolidation on the novel word trials is somewhat puzzling. Based on our results in Chapter 3, we expected the nap group to show target preference after sleeping. Nonetheless, no significant change was observable in either of the group. It seems peculiar that infants who recognised a differently coloured object were not able to identify the original object. Hence, it is more likely that after the familiar and the generalisation trials they lost their interest in the study and did not participate in the task.

Experimenters were not blind to group membership in our study, which might have affected our results. As we explained it in Chapter 3, experimenters who had experience with children could judge the group membership of the infants on the basis of their behaviour. We attempted to minimise any confounding effects by using a predefined script during the interactive training phase. Moreover, during the on-screen training and testing phase the experimenter was in the control room. In addition, parents were blind to the hypothesis of the study; thus, it was unlikely any of these factors influenced the results.

To conclude, our study implies that during sleep it is not just a passive consolidation that takes place in the brain of an infant, but an active ‘memory evolution’ (Stickgold & Walker, 2013). During this process, the key aspect of the category, which is a constant shape in the current study, is retained in association with the label while irrelevant information is forgotten.

CHAPTER 5. NORMAL SLEEP IN INFANTS AND TODDLERS

In this chapter, our goal was to provide some data on normal sleeping in infants and toddlers. For data collection we used our newly developed family friendly sleep diary, the SNORI. We also tested how nursery attendance influences sleep, along with other variables (age, breastfeeding and co-sleeping with the parents or siblings) that have been shown to affect infants' sleeping. We found comparable values to previous studies, indicating that the SNORI is an appropriate tool for investigating infants' sleep. Furthermore, we showed that there is a decline in nap time and nap-sleep proportion between the ages 6 and 31 months, whereas night time sleep and awakening time during night did not change within this period. In addition, our results suggest that nursery attendance has an impact on sleep; shorter sleep and nap times and more time spent awake during night was associated with day care.

Introduction

The sleep of infants and young children is often a puzzle for parents with the lack of well-established norms and evidence-based practices (specifically regarding the optimal timing, duration and bed time routines) not being of much help. One key point is to adapt the methodology to the busy life of families such that it makes data collection smoother and less demanding, yet fairly accurate. Thus, in this study we introduce the Sleep and Naps Oxford Research Inventory (SNORI) which is a sleep diary designed specifically for family friendly usage. Furthermore, we provide data collected with the SNORI in 6-31 month typically developing infants, a relatively under-investigated age group in terms of sleep research. Since this age group is often in day care, our other goal was to study how this affects sleep patterns.

Several sleep variables go through developmental changes. In a meta-analysis of observational studies between the ages 2 months and 12 years, a clear reduction with age is noticeable in sleep duration, the number of night awakenings and the number of daytime naps.

Sleep duration showed the steepest decline in the first 6 months of life. The data concerning night awakenings were highly variable, possibly due to many impinging environmental factors (breastfeeding, bed sharing). However, the data still showed a declining trend from birth to 2 years. Between these ages, the number of naps also decreased (Galland et al., 2012). A cross-cultural study found significant differences between predominantly-Asian and predominantly-Caucasian countries in the sleeping pattern of infants. In Asian cultures, parents reported later bedtimes and shorter sleep duration. However, the difference in daytime sleeping was not statistically significant (Mindell, Sadeh, Wiegand, How & Goh, 2010).

The vast majority of the studies in the above mentioned age group used sleep diaries or questionnaires to assess sleeping habits. These methods have been shown to be reliable (Kaplan, Talbot, Gruber & Harvey, 2012; Sadeh, 2004; Werner, Molinari, Guyer & Jenni, 2008), although they are not as accurate as actigraphy or polysomnography in which activity levels or brain waves together with eye movements and muscle tone are measured during sleep, respectively (Galland et al., 2012). Sleep diaries are used for several days in which the subjects or the care givers have to record bedtimes, wake-up time and any awakenings during the night. They also provide the opportunity to make comments on the circumstances of sleep. Sleep questionnaires ask for the individual's general sleep and wake times, usually distinguishing between weekdays and weekends. Werner et al. (2008) compared these two to each other and to actigraphy in 4-7 year old children. While actigraphy and sleep diaries showed a remarkable agreement on sleep start, sleep end and actual sleep time, data were less consistent on wake times during the night. On the other hand, questionnaire data did not accord sufficiently with either actigraphy or sleep diaries in their study. Even though sleep diaries may not be the most accurate and objective measure, they possess the advantage of being time and cost-effective (Werner et al., 2008). Thus, for a large-scale study such as the present one, using diaries seemed to be the most sensible format facilitating compliance and accuracy.

The central importance of childhood sleep is widely acknowledged. Mental development has been associated with different sleep measures (for review, see Ednick et al., 2009) in infants. Similar correlations exist with motor development; however, data on this are more inconsistent (Ednick et al., 2009). Touchette et al. (2007) found that short sleep duration predicts lower performance on cognitive neurodevelopmental tests and hyperactive-impulsive behaviour. Moreover, vocabulary size was predictable from the proportion of daytime and night-time sleep (Dionne et al., 2011). It is not just sleep duration and certain EEG characteristics that are related to mental development, but also circadian sleep regulation (Dearing, McCartney, Marshall & Warner, 2001). Sleep contributes to physical health too, short sleepers report poorer health (Magee, Gordon & Caputi, 2014). In addition, many studies warn about the danger of becoming overweight as a consequence of insufficient sleep (Chen, Beydoun & Wang, 2008; Liu, Zhang & Li, 2012; Scharf & DeBoer, 2014; Touchette et al., 2008). Therefore, promoting healthy sleeping may have a favourable effect on both mental and physical health.

The number of infants attending day care has been increasing (Brind et al., 2014); however, its effects on sleeping has not yet been investigated. Even though many studies report the sleep of children attending nurseries (e.g. Ward, Gay, Anders, Alkon & Lee, 2008), the comparison with infants who are not in day care, and the comparison between nursery and non-nursery days, have yet to be undertaken. Poorer sleep in day care infants would warrant further research in order to be able to achieve the optimal circumstances in day care services.

Our main goal in this study was to collect data with our newly designed sleep diary, the SNORI, to examine its convenience. Moreover, we intended to garner a picture of the sleeping patterns of typically developing infants and toddlers in the Oxfordshire area—the area from where the vast majority of participants in all of this thesis's studies come. In addition, we aimed to investigate some of the factors influencing sleep. In particular, nursery attendance, which has yet to be investigated.

Methods

Two hundred and eighty one families participated in this study, mainly from the Oxfordshire area. Families were recruited via phone or e-mail or in person when they visited the laboratory for another experiment. Birth history was obtained and parents were asked about any concerns about developmental delay. Criteria for inclusion to the study were that parents did not indicate any developmental problems and that the infants were born full term (> 37 weeks). The study was approved by University of Oxford Central University Research Ethics Committee (MSD/IDREC/C2/2012/11).

Questionnaires

Sleep and Naps Oxford Research Inventory (SNORI)

The SNORI is a sleep diary designed to be completed over ten days. Ten days were chosen because even if there are a few days of data have to be excluded, both weekends and weekdays are represented. Moreover, this data collection methodology increases the chances of having at least five days of consecutive data that would make an analysis of the circadian rhythm possible. Additional questions concerning breastfeeding, travel between time zones, milestones in the infant's motor development and a survey about the most common health related factors (including current medication) that may affect the child's sleep are also included in the inventory. The SNORI is an easy to use, handy sleep diary in the form of an A/5 booklet that fits easily into handbags and onto bedside tables. The diary contains a separate page for each day, with visual aids to distinguish daytime and night time. Parents are requested to draw a line to a time scale that allows for an accuracy of 15 minutes, to indicate when their child had a nap or slept. Parents were instructed to indicate the time when they put their child to bed with a down arrow, and to fill in the time when their child was sleeping with a continuous line. If they woke up their child, they were asked to indicate it with an up arrow. If their child woke up of their own accord, they did not have to draw anything else. They were also asked to write down (under the line) the place and circumstances of the sleep or nap (e.g. bedroom, pushchair, car) and to take note of night awakenings and nursery days. Parents were specifically asked every day whether there was anything unusual that day which might have disrupted their child's sleep. Within the SNORI, there is ample space to make corrections and or note additional information the parent may want to record. The colourful design of the SNORI helps to make it even more family friendly, as a result of which parents were generally pleased with its format. Many of them provided feedback that they preferred this format (i.e. drawing a line to a time scale) compared to a sleep diary in which they were asked to note down the specific sleep and wake up times. In this way, they were also able to see any regularity in their child's sleep patterns. The SNORI is also available to view online and download from the Oxford BabyLab website. For children attending nursery, nursery staff completed the SNORI during nursery hours.

Oxford Communicative Development Inventory (OCDI)

The OCDI (Hamilton et al., 2000) is a word list consisting of the 416 words which are most commonly acquired in infancy. Parents are asked to indicate whether their child understands (comprehension), or understands and can say (production), a particular word. OCDI comprehension and OCDI production scores are derived by counting the number of words a child is assumed to understand or say. While the estimation of vocabulary production is fairly straightforward, it might be argued that parents are less precise in estimating their child's understanding of words. However, it has been shown that parents are equally accurate in assessing comprehension (Styles & Plunkett, 2009).

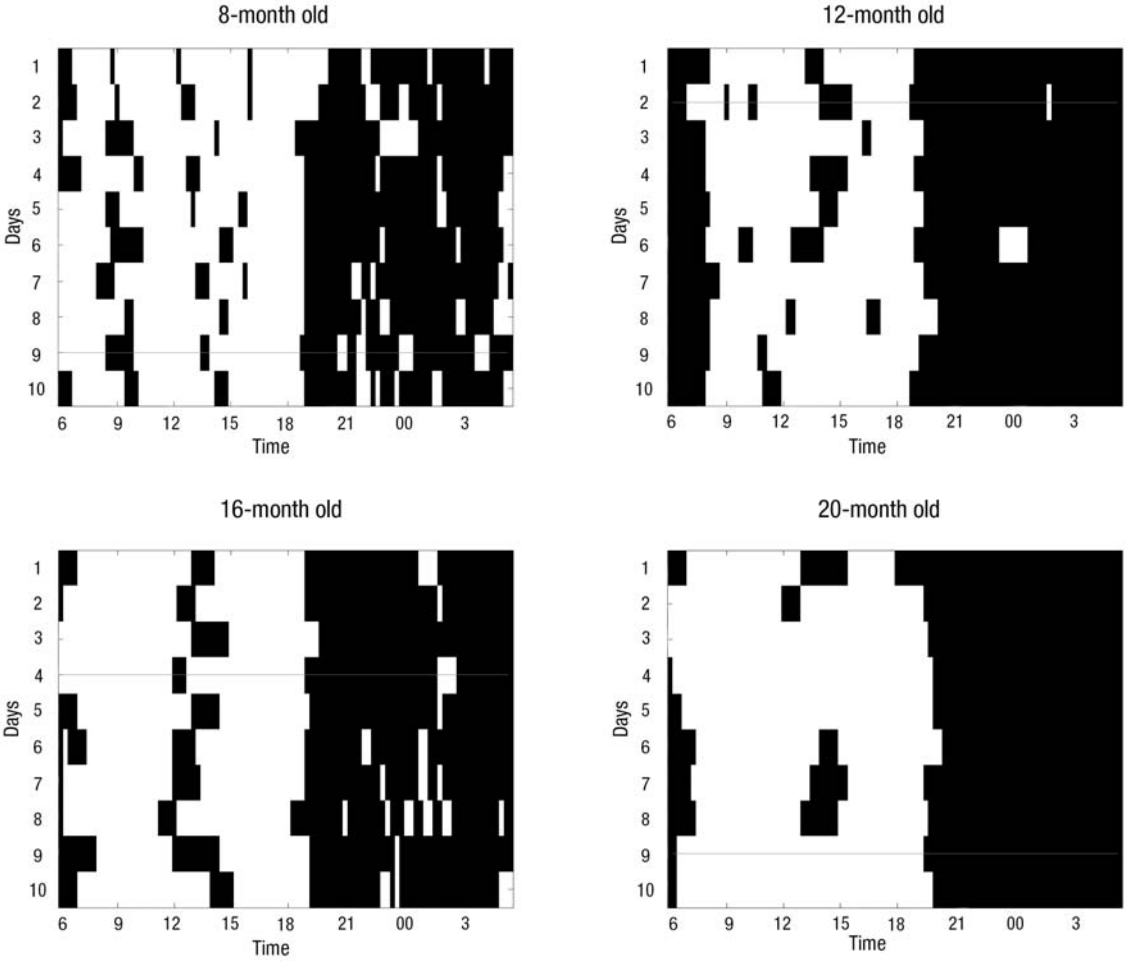
Data processing

The SNORI data were manually binary coded into Excel (Microsoft Office, 2013, Redmond WA) and processed using MATLAB (version 8.2.0.701, R2013b, The MathWorks, Inc., Natick, MA). Any data returns for days that parents considered ‘special’ (e.g. due to illness or travelling) were excluded. Only those children for whom we had at least seven days of data, who did not take any medication and did not travel between time zones in the previous month of the study were included in the analysis. A diagram (Figure 5.1) of sleep patterns was created for each infant that was checked manually to remove any days with anomalies. Such presentation of the data helps researchers to obtain a picture of intra- and inter-individual variability.

Onset of the main sleep was automatically derived for each day on the basis of a combination of variables including time of day and length of breaks in sleep using custom MATLAB routines. The algorithm used is as follows: first, we identified all the sleep starts and sleep ends within the data. Next, we defined a window between 6pm and 8am, as this is the time window that most probably contains the main period of sleep (i.e. longest sleep period that is normally during the night in our target age groups). We identified the first sleep start and the last sleep end within this periods that were preliminary assigned to the start and the end of the main sleep, irrespective of the time spent awake between them. Then, it was checked whether another sleep end preceded the main sleep start within the 4pm-6pm period. If yes, and the difference was less than 1.5 hours between the main sleep start and the preceding sleep end, the corresponding sleep start replaced the main sleep start. Similarly, it was checked whether another sleep start followed the main sleep end within the 8am-10am period. If yes, and the difference was less than 1.5 hours between the main sleep end and the following sleep start, the corresponding sleep end replaced the main sleep end. If the difference was more than

1.5 hours in any of the cases, they were considered to be daytime naps. The following sleep variables were derived for each day and were averaged within infants.

- Sleep duration: length of the main sleep
- Number of awakenings during the night
- Time spent awake during the night
- Total sleep time: sleep duration – time spent awake during the night
- Nap time: total duration of sleep other than the main night time sleep
- Nap-sleep proportion: nap time/sleep duration



8-month old

12-month old

16-month old

20-month old

Figure 5.1. Sleep patterns of four children. Periods spent asleep are marked black. The line signs that the parent indicated that day as special.

Statistics

Statistical analyses were conducted in R (version 3.1.0, R-Team, 2008). To analyse the possible effects of age and nursery on the sleep variables, linear regression was performed using the lm command of R. Because it is already known that breastfeeding and bed-share influence sleep (DeLeon & Karraker, 2007; Hunsley & Thoman, 2002; Thoman, 2006; Touchette et al., 2005) we included these variables into our analyses. Variable inclusion was stepwise based on theoretical considerations. Models were compared using the anova function available in R. If a variable did not improve model fit, it was excluded from the model. Only the final model fit and parameters are presented. In children about whom we obtained data for both nursery and no-nursery days, we compared the sleep variables with paired sample t-test.

Results

The data of 269 children (133 males, 136 females) were analysed between the age range of 6.47 and 31.17 months. All children in the sample had naps habitually. The average age of mothers was 35.52 years (SD = 4.4, range: 21.91 – 51.02), while it was 37.27 years for the fathers (SD = 5.32, range: 26.73 – 59.28). Mothers spent 16.26 years (SD = 2.23, range: 6 – 19), fathers spent 15.69 years (SD = 2.23, range: 11 – 19) in education. The majority of the parents (mothers: 85.86%, fathers: 73.26%) had obtained a university degree (> 14 years). Out of all children, 57 were still breastfed, 195 had been breastfed but stopped before the age of the examination and 21 had not been breastfed at all. 63% of the children received day care and 17% shared beds at least occasionally with either or both of their parents.

Sleep duration and total sleep time

Sleep duration and total sleep time were not associated with age or nursery, however, breastfeeding and bed share were significant predictors (see model parameters in Table 5.1).

Regarding sleep duration, the final model was significant (F (258) = 4.26, p = .02, R^2 = .03) with breastfeeding and bed share as predictors. Infants who were breastfed or shared beds with their parents had sleep of a shorter duration. Regarding total sleep time, in the multiple regression analysis, age and nursery did not improve model fit, therefore, they were excluded from the final model. The model was statistically significant (F (258) = 14.4, p < .001, R^2 = .1). Breastfeeding and bed-share were both significant predictors of total sleep time. Children who were breastfed or shared beds with their parents slept less during the night. For the whole sample, mean sleep duration was 678.2 (SD = 49.78) minutes, with mean total sleep time being 659.3 (SD = 52.2) minutes.

Table 5.1. *Sleep duration and total sleep time: parameter estimates*

	Sleep duration			Total sleep time		
	Estimate	SE	t-value	Estimate	SE	t-value
Intercept	683.64	3.62	188.97***	669.26	3.66	182.87***
Breastfeeding	-14.51	7.47	-1.94^{+}	-21.86	7.56	-2.89**
Bed-share	-14.97	8.05	-1.86^{+}	-32.84	8.14	-4.03***

Notes. $p < .1^{+}$, p < .05*, p < .01**, p < .001***

Nevertheless, both sleep duration (t (117) = 2.61, p = .01) and total sleep time (t (117) = 5.04, p < .001) differed significantly between nursery and no nursery days. Nursery infants slept about half an hour less on nursery days (M = 627.19, SD = 86.08) compared to non-nursery days (M = 661.47, SD = 58.84).

Total nap time and nap-sleep proportion

In the final model, age, nursery and an interaction between age and nursery were included as predictors for both independent variables. Both models were significant, the model predicting total nap time explained 26% of the variance (F (262) = 30.78, p < .001), while the model predicting nap-sleep proportion accounted for 22.55% of the variance (F (262) = 25.43, p < .001). Model parameters are shown in Table 5.2. Children who went to nursery napped half an hour less according to the model and they also had a lower nap-sleep proportion. A steady decrease with age can be observed in both variables. Infants at 8 months had an average nap time of 2.44 hours that dropped to 1.15 hours by the age of 30 months. Similarly, nap-sleep proportion declined from 22% at the age 8 months to 11% at the age 30 months. The means, SDs, 2nd and 98th percentiles by age are shown in Table 5.3. In addition to which, we found a significant interaction between age and nursery in both cases, as depicted in Figure 5.2. Children who were not in day care showed a steeper decline in total nap time and nap-sleep proportion with age.

No significant difference was found in the within-subject comparison of nursery and no-nursery days in either total nap time (t (117) = 0.4, p = .69) or nap-sleep proportion (t (113) = 0.76, p = .45).

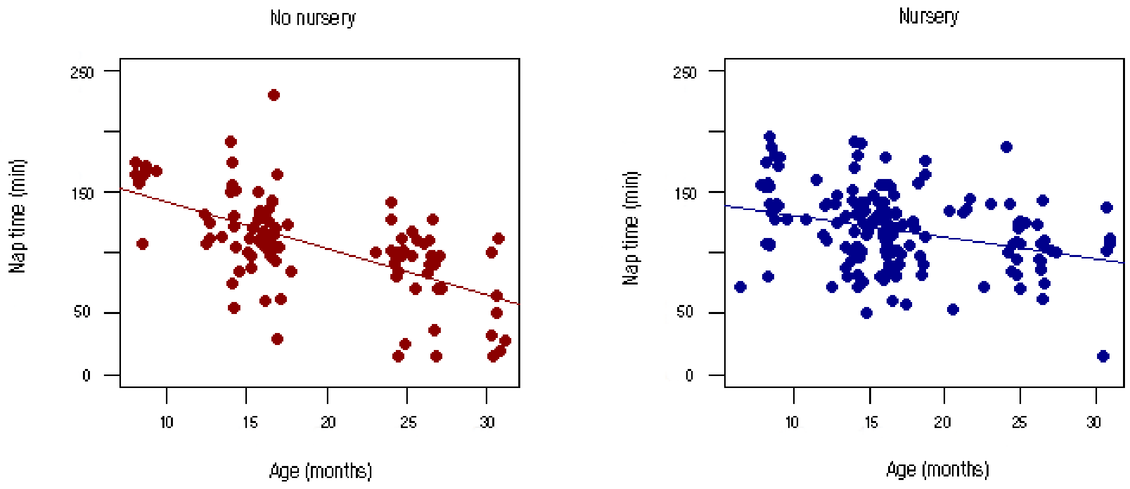


Figure 5.2. The association between nap time and age in children who attend nursery versus who do not.

Table 5.2. *Total nap time and nap-sleep proportion: parameter estimates*

	Total nap time			Nap-sleep proportion		
	Estimate	SE	t-value	Estimate	SE	t-value
Intercept	181.14	9.81	18.46***	0.27	0.02	16.02***
Age	-3.85	0.48	-8.03***	-0.01	0.001	-7.03***
Nursery	-31.88	12.41	-2.57*	-0.04	0.02	-1.95^{+}
Age:nursery	2.07	0.64	3.21**	0.003	0.001	2.69**

Notes. $p < .1^{+}$, p < .05*, p < .01**, p < .001***, SE – standard error.

Table 5.3. *Descriptive statistics of total nap time and nap-sleep proportion by age.*

Age group *(months)*	Number of children	Total nap time (*hours*)				Nap-sleep proportion			
		Mean	SD	2nd percentile	98th percentile	Mean	SD	2nd percentile	98th percentile
8	28	2.44	0.54	1.26	3.20	0.22	0.05	0.12	0.3
12	13	2.09	0.37	1.35	2.62	0.19	0.04	0.11	0.25
14	49	2.01	0.58	0.91	3.21	0.19	0.06	0.08	0.34
16	79	1.96	0.47	1.00	2.85	0.18	0.05	0.1	0.27
18	17	1.86	0.55	0.99	2.88	0.17	0.06	0.09	0.29
24	25	1.66	0.57	0.33	2.77	0.16	0.05	0.03	0.25
26	30	1.60	0.45	0.45	2.24	0.15	0.04	0.04	0.21
30	13	1.15	0.74	0.25	2.19	0.11	0.07	0.02	0.21

Notes. Data for age groups with n > 10 are shown. SD – standard deviation.

Awakening time and awakening number

To normalise the awakening time and frequency during night variables, we applied a square root transformation. Means presented are back-transformed. For predicting awakening time, nursery, breastfeeding and bed-share were the predictors included in the final model with the interaction term of breastfeeding and bed-share (F (256) = 2.595, p < .001, R^2 = .15). On the other hand, nursery and bed-share as predictors resulted in the best model for awakening frequency (F (263) = 24.98, p < .001, R^2 = .16). Infants who attend day care spent more time awake during the night, similarly to those children who are breastfed and who co-sleep. Day care and co-sleeping also resulted in more frequent awakenings. The median for awakening time in the sample was 10 minutes, for awakening number 0.388. Model parameters are in Table 5.4.

Table 5.4. *Model parameters for awakening time and awakening frequency*

	Awakening time			Awakening frequency		
	Estimate	SE	t-value	Estimate	SE	t-value
Intercept	2.12	0.28	7.59***	0.41	0.05	8.66***
Breastfeeding	1.01	0.46	2.22*			
Bed-share	2.64	0.51	5.14***	0.4	0.07	5.38***
Nursery	1.04	0.34	3.10**	0.23	0.06	4.02***
Breastfeeding:bed-share	-1.69	0.92	-1.83^{+}			

Notes. $p < .1^{+}$, p < .05*, p < .01**, p < .001***, SE – standard error.

Within subject comparisons revealed that children spent significantly more time awake during night on nursery days (M = 19.62 min) compared to non-nursery days (M = 12.96 min, t (115) = -2.59, p = .011). Furthermore, there was a tendency to wake up more often during night on days when the children received day-care (M = 0.62) in contrast with days at home (M = 0.5, t (117) = -1.72, p = .089).

Discussion

In this study, we provided the first data collected with the SNORI, a new sleep diary designed for family use. We described the sleep patterns of typically developing British infants' from the Oxfordshire area between the ages 6-31 months. A remarkable decrease was observed in napping time and nap-sleep proportion, while night-time sleep and awakenings did not change significantly within this age group. Importantly, we found that nursery attendance has a substantial impact on infants' sleep, meaning infants in day care had shorter sleep and naps and more awakenings during the night.

Our results are similar to other studies', implying that the SNORI is a reliable tool to investigate sleep in infancy. In addition, we provide detailed and age specific data on the sleep patterns of infants and toddlers. Sleep duration in our sample seemed to be less than in the meta-analysis of Galland et al. (2012), but similar to the study of the Avon Longitudinal Study of Parents and Children (ALSPAC) cohort as reported by Blair et al. (2012). The children in that cohort were from South West England and they were born in 1991-1992 (in contrast to 2011-2013 in our sample). This might mean that no further reduction is observable in sleep duration with time, as was noted previously (Blair et al., 2012; Iglowstein et al., 2003), or it may be the consequence of cultural similarities between the two samples. We did not find a declining trend in number of awakenings contrary to Galland and colleagues' model (Galland et al., 2012). Interestingly, all children taking part had regular naps, which was not the case in the ALSPAC study (Blair et al., 2012). It is important to note that older toddlers were under-represented in our sample. Daytime sleep duration mainly converged between the present and the ALSPAC study (Blair et al., 2012); however, in the 18 month age group we found slightly higher values (1.86 versus 1.5 hours). Daytime sleep duration showed a clear decrease with age between the ages 6-31 months. Since no other sleep variable showed a similar relationship in our study, our findings suggest that in late infancy and early toddlerhood daytime sleep goes through the most pronounced developmental changes.

To the best of our knowledge, the effects of nursery on sleep have not yet been investigated. However, our results suggest it significantly influences children's sleep patterns. Infants who attended nursery slept about 30 min less during the day. They also woke up more and spent more time awake, which explains the difference in night-time sleep. The fact that nursery and no-nursery days differed significantly within infants who regularly attend day-care suggests a direct effect of nursery on night-time sleep. On the other hand, we did not find a difference in daytime sleep between nursery and no-nursery days. Infants might get used to the stricter and less individualised napping schedule and nap on no-nursery days accordingly. Alternatively, it might be a consequence of another unknown factor associated with receiving day-care.

The factors leading to sleep disruption are unknown. One possible cause is that nursery may be a source of stress for infants. In a study of English children, participants who received nursery care were more likely to have behavioural problems (Stein et al., 2013). As the employment of both parents is increasing, investigating further nursery related sleep problems and finding ways in which day-care can minimise any potential disruption is of fundamental interest to society.

As it was expected, breastfeeding was associated with longer time spent awake during the night, shorter total sleep time and shorter sleep duration. Most probably, shorter total sleep time was a consequence of longer awakening time. However, sleep duration was also shorter in breastfed infants, which may be due to their later bed time. Neither awakening frequency, nor daytime sleeping was associated with breastfeeding. Less efficient self-soothing might contribute to longer awakening times, and thus, shorter total sleep time (Burnham, Goodlin-Jones, Gaylor & Anders, 2002; Hiscock, 2010; Sadeh, Tikotzky & Scher, 2010). Further research should decide whether the longer time spent awake is due to less efficient self-soothing in breastfed infants or breastfeeding takes longer than e.g. formula feeding.

Our study has some limitations mainly due to methodology. Sleep diaries have been shown to be fairly accurate (Kaplan et al., 2012; Werner et al., 2008), however, they cannot provide as accurate data as physiological measures. It is especially true in measuring the number and the duration of awakenings since parents are often not aware of their children waking up during the night. Furthermore, our study design was cross-sectional, therefore we are unable to infer causal relationships between sleep and examined factors. Most importantly, our sample consisted of Caucasian, mainly middle-class British families from the Oxfordshire area, thus, it is not possible to generalise our results to infants from different cultural and socio-economic backgrounds.

In sum, our study provides valuable data on the sleeping patterns of typically healthily developing infants that may serve as a norm for worried parents and childcare specialists. It also introduces the SNORI data gathering methodology, which is a family friendly alternative to the usual sleep diaries. As the data collected with the SNORI is comparable with that of other studies, we claim that SNORI is well suited to wider use in further studies investigating the relationship between sleep and vocabulary development. Furthermore, our findings urge that there should be additional studies undertaken exploring the relationship between nursery attendance and sleep patterns in order to be able to provide infants with the best possible circumstances that ensure healthy mental and physical development.

CHAPTER 6. ASSOCIATIONS BETWEEN SLEEP VARIABLES AND VOCABULARY DEVELOPMENT*

The facilitating role of sleep for language is well-attested in adults and to a lesser extent in infants and toddlers. However, the longitudinal relationship between sleep patterns and early vocabulary development is not well understood. In this chapter, we investigate how different measures of sleep are related to the development of vocabulary size in infants and toddlers. Day and night-time sleeping patterns of infant and toddlers were compared with their concurrent and subsequent vocabulary development. Sleep assessments were conducted using the SNORI (see Chapter 5). Sleep measures were used as predictors in a multi-level growth curve analysis of vocabulary development. The length of daytime naps was positively associated with both expressive and receptive vocabulary growth, whereas the length of night-time sleep was negatively associated with the rate of expressive vocabulary growth. These results point to a longitudinal relationship between sleep and language development.

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*Parts of this study has been submitted and are currently under review as:
Horvath, K., Plunkett, K. (in review). Frequent daytime naps predict vocabulary growth in early childhood. J Child Psychol Psyc.

Introduction

The importance of sleep for cognitive development in infancy has come under close scrutiny in recent years. Some studies have focused specifically on the impact of sleep on language development (Friedrich et al., 2015; Gomez et al., 2006), including our studies described in Chapters 3 and 4, whilst others have focused on other aspects of the development of memory (Seehagen et al., 2015), or how early measures of sleep are associated with later cognitive outcomes (Ednick et al., 2009). In this article, we ask whether there is a longitudinal relationship between infant vocabulary development and previously established patterns of sleep. Investigating links between sleep patterns and lexical development in infancy has the potential to contribute to our understanding of the manner in which sleep supports early language development and may allow us to identify groups that are at risk and provide early intervention.

The facilitating role of daytime naps on memory consolidation, generalisation and word learning in infancy has been confirmed by several studies (Friedrich et al., 2015; Gomez et al., 2006; Kurdziel et al., 2013; Seehagen et al., 2015), including our studies described in Chapters 3 and 4. To investigate the relationship between these cognitive processes and naps in infancy, researchers use study designs where they compare the performance of a nap group to a wake group. Seehagen et al. (2015) demonstrated the beneficial effect of a nap on declarative memories assessed with the deferred imitation task in 6 and 12 month old infants. Naps also facilitated the abstraction of a rule in a language learning context in 15 month olds (Gomez et al., 2006; Hupbach et al., 2009), though this was not observed for 2.5 year olds (Werchan & Gomez, 2014). Sleep has been shown to have a facilitating role on word learning and generalisation of word meanings in 9-16 month olds in an event related potential study (Friedrich et al., 2015) and eye-tracking studies provide evidence that naps facilitate both word learning (see Chapter 3) and word generalisation (see Chapter 4) in 16 month old infants.

The evidence suggests that sleep measures can also predict later cognitive outcomes. Ednick et al. (2009) reviewed thirteen studies investigating the longitudinal relationship between mental development and sleep in the first year of life. The reviewed studies used different methods for sleep assessment and mental assessment and they were carried out in infants at different ages. Moreover, some of them also included premature infants or infants with developmental delay. All of these factors may have contributed to the difficulty in drawing definite conclusions. However, most of the studies found a predictive relationship between some kind of sleep measure (e.g. number of arousals, longest sleep period, sleep efficiency, REM storms, total sleep, total night-time sleep, etc.) and mental development. These associations were not exclusive to the first year of life. Short sleep duration in toddlerhood was linked to poorer cognitive performance at school entry (Touchette et al., 2007), while circadian sleep regulation (i.e. the extent to which the sleep-wake cycle is explained by a 24-hour rhythm) at 19 months was positively associated to cognitive performance (Dearing et al., 2001). Of course, it is not possible to conclude from these studies whether the correlation between sleep and cognitive outcome reflects a true causal relationship or an overall maturational status which affects both (Ednick et al., 2009).

The relationship between infant sleep and vocabulary development has received less scrutiny. Circadian sleep regulation in 7 and 19 month olds was positively correlated with language development at 36 month (Dearing et al., 2001) and a greater proportion of night-time sleep to daytime sleep at 12 months correlated positively with a larger productive vocabulary at 26 months (Bernier, Carlson, Bordeleau & Carrier, 2010). Similarly, sleep-wake consolidation, as defined by the proportion of daytime and night-time sleeping at 6 and 18 month of age was negatively correlated with later vocabulary scores. Moreover, children with language delay at 5 years had poorer sleep consolidation at 6 and 18 months. Genetic analyses of mono and dizygotic twins showed that while sleep consolidation was highly heritable at 6 months, in 18 month olds it was mainly due to shared environmental factors. Furthermore, the association between sleep and language showed a similar pattern, being genetically influenced at 6 months with a more significant role of the environment in older children (Dionne et al., 2011).

In the present study, our aim was to investigate further the relationship between vocabulary development and sleep in infants and toddlers, with a focus on individual differences as opposed to maturational changes in sleep patterns as in Dionne et al. (2011). Using growth curve modelling, we studied how patterns of sleep during different times of the day influence the growth of individual vocabulary sizes both in terms of the initial starting point and the pace of development. In particular, we asked whether daytime napping habits and night-time sleep play the same facilitating role for infant vocabulary development.

Methods

Families were recruited via phone, e-mail or in person when they visited the laboratory for another experiment. Criteria for an infant's inclusion in the study were that the parents indicated that to their knowledge their child has no developmental problems and that infants were the result of full term births (> 37 weeks). As part of an initial assessment, parents were asked to fill in the Sleep and Naps Oxford Research Inventory (SNORI) and the Oxford Communicative Development Inventory (Hamilton et al., 2000). The questionnaires, information about the study and a consent form were sent by post or delivered in person and returned by post. Follow-up vocabulary assessments were scheduled 3 and 6 months after the initial assessment, again using the Oxford Communicative Development Inventory (OCDI). Multiple deviations from the intended follow-up resulted in variability in the timing and number of vocabulary assessments for each infant. However, all the infants reported in the study had an initial sleep and vocabulary assessment between 7.73 and 37.83 months of age, follow-up assessments of vocabulary varied between two to eight occasions (median = 3). Participants without follow-up data were also included as their data contributed to the initial assessments.

The study was approved by University of Oxford Central University Research Ethics Committee (MSD/IDREC/C2/2012/11).

Questionnaires

Sleep and Naps Oxford Research Inventory (SNORI)

The SNORI is a sleep diary to be completed over ten days. It was designed to be family friendly and easily usable. For a broader description see Chapter 5.

Oxford Communicative Development Inventory

The OCDI (Hamilton et al., 2000) is a word list consisting of the 416 words that are most commonly acquired in infancy. Parents are asked to indicate whether their child understands (comprehension), or understands and can say (productions), a particular word. For more description see Chapter 5.

Data processing

The SNORI data were manually binary coded into Excel (Microsoft Office, 2013, Redmond WA) and processed using MATLAB (version 8.2.0.701, R2013b, The MathWorks, Inc., Natick, MA). Any data returns for days that parents considered ‘special’ (e.g. due to illness or travelling) were excluded. Only those children for whom we had at least seven days of data, who did not take any medication and did not travel between time zones in the previous month of the study were included in the analysis. A diagram (Figure 5.1) of sleep patterns was created for each infant that was checked manually to remove any days with anomalies. Such presentation of the data helps researchers to obtain a picture of intra- and inter-individual variability.

Onset of the main sleep was automatically derived for each day on the basis of a combination of variables including time of day and length of breaks in sleep using custom MATLAB routines. For detailed description see Chapter 5. The following sleep variables were derived for each day and were averaged within infants.

- Sleep duration: length of the main sleep
- Time spent awake during the night
- Total sleep time: sleep duration – time spent awake during the night
- Nap time: total duration of sleep other than the main night-time sleep

Statistical analyses

Statistical analyses were conducted in R (version 3.1.0, R-Team, 2008). To analyse the possible effects of different predictors on the growth of receptive and expressive vocabulary, we used multilevel growth modelling following the procedures as described in Singer and Willett (2003). This approach takes into account both individual change (level 1 sub-model) and inter-individual variability in this change (level-2 sub-model). Growth curve modelling has the additional advantage of accommodating longitudinal data which is unbalanced and where the intervals between data collection points differ. We used generalised linear mixed effect modelling with the *glmer* function of the *lme4* package for R (Bates, Maechler, Bolker & Walker, 2015). Outcome measures were the OCDI comprehension and production scores which are binomially distributed (i.e. how many words an infant understands, or understands *and* can say, out of 416; where the minimum is 0 when an infant does not know any of the words). We used a cube root transformation to normalise the distribution of time spent awake. The age for the OCDI outcomes was centred to 12 months. Total sleep time, nap time and time spent awake during night were standardised thereby reducing correlations between sleep variables to an acceptable level ($|r| < .5$). We provide results for the unconditional means models, the unconditional growth models and the full models with the final predictors selected using backward elimination. Predictors were removed stepwise and goodness of fit was compared across the models using the *anova* function in R. If model fit significantly worsened (as assessed comparing the log likelihoods), we reinstated the predictor even if it was not significant. The predictors used for vocabulary outcomes are listed in Table 6.1 with accompanying glosses. We intended to test for interaction effects on the basis of our findings in Chapter 5. However, introducing them into the model caused failure to converge, most probably due to the larger number of terms specified relative to the sample size. Hence, we only tested main effects for the initial status and the rate of change.

Table 6.1. *Predictors used for growth curve modelling of vocabulary outcome.*

Variable	Explanation
Age at OCDI	Age at vocabulary assessment
Total sleep time	Average time slept during the night (time spent awake was excluded)
Nap time	Average time slept during the day
Time spent awake	Average time the infant spent awake during the night
Sex	
Breastfeeding	Was the infant breastfed at the time of the sleep assessment?
Nursery	Did the infant attend nursery at the time of the sleep assessment?

Results

Participants

Two hundred and forty six children (male: 121, female: 125) took part in the study. Children were between 7.73 – 37.83 months old at the initial assessment (M = 17.89, SD = 6.34). Fifty seven of them were breastfed and 159 attended nursery at the initial assessment.

The vast majority of mothers had at least an undergraduate degree (222). The average nap time was 114.67 (SD = 32.37) minutes, total sleep time was 659.37 (SD = 51.61) minutes, time spent awake was 18.84 (SD = 26.13) minutes. At the initial OCDI assessment, the average receptive vocabulary size was 184.3 (SD = 139.08, range = 0–416) and expressive vocabulary score was 102.7 (SD = 137.27, range = 0–416).

Cross-sectional associations between sleep and vocabulary size

To investigate whether the sleep variables are associated with vocabulary size at the initial assessment independently of age, we performed a preliminary multiple regression with age and sleep variables included as potential predictors of vocabulary size. As expected, age was a highly significant predictor of expressive and receptive vocabulary scores (see Table 6.2). For comprehension, there was a significant negative association with total sleep time, indicating that infants who sleep more tend to have smaller receptive vocabularies. For production, none of the sleep variables, including total sleep time, reached significance. Model parameters are shown in Table 6.2. The full model for comprehension explained 78.64% of the variance ($p < .001$) and for production, adjusted R^2 was 0.68 ($p < .001$).

Table 6.2. *Model parameters of the multiple regression analyses predicting vocabulary outcome from cross-sectional variables*

	Estimate	SE	t value	p value
Comprehension				
Intercept	-175.22	14.02	-12.50	< .001
Age	18.96	0.75	25.21	< .001
Nap time	0.08	4.88	0.02	.988
Sleep time	-9.98	4.86	-2.05	.041
Time spent awake during the night	-7.70	4.70	-1.64	.103
Production				
Intercept	-227.50	16.55	-13.75	< .001
Age	17.59	0.89	19.82	< .001
Nap time	8.79	5.76	1.53	.128
Sleep time	-7.07	5.74	-1.23	.219
Time spent awake during the night	-9.16	5.55	-1.65	.100

Predictive relationships between sleep and vocabulary development

To explore how sleep and other control variables predict the initial status (reference: comprehension/production score at 12 months of age) and rate of receptive and expressive vocabulary development, growth curve modelling was used, allowing random effects for both initial status and rate of growth across children. After constructing the individual means and growth models, we stepped in all sleep variables as well as sex, breastfeeding and nursery attendance. Insignificant predictors were removed stepwise provided this did not result in a poorer model fit. Model parameters for the unconditional mean, growth and final models are shown in Tables 6.3 and 6.5 for comprehension and production respectively. Model parameters of the full models (including all the variables analysed) are in Appendix 1 and 2.

For comprehension, nap time along with sex and nursery attendance had a significant effect on the rate of development. Children who took longer daytime naps had a higher rate of receptive vocabulary growth (see Figure 6.1), as did children who attended nursery. Nursery attendance had a significant effect on initial status as well; the model predicts that children attending nursery had larger receptive vocabulary size at 12 months (Figure 6.2). Although not significant in itself, the removal of the effect of breastfeeding on the initial status resulted in a poorer model fit. Therefore, breastfeeding was included in the final model. Residual plot indicates a good model fit (Figure 6.3). Model predicted values with confidence intervals are plotted in Figure 6.4.

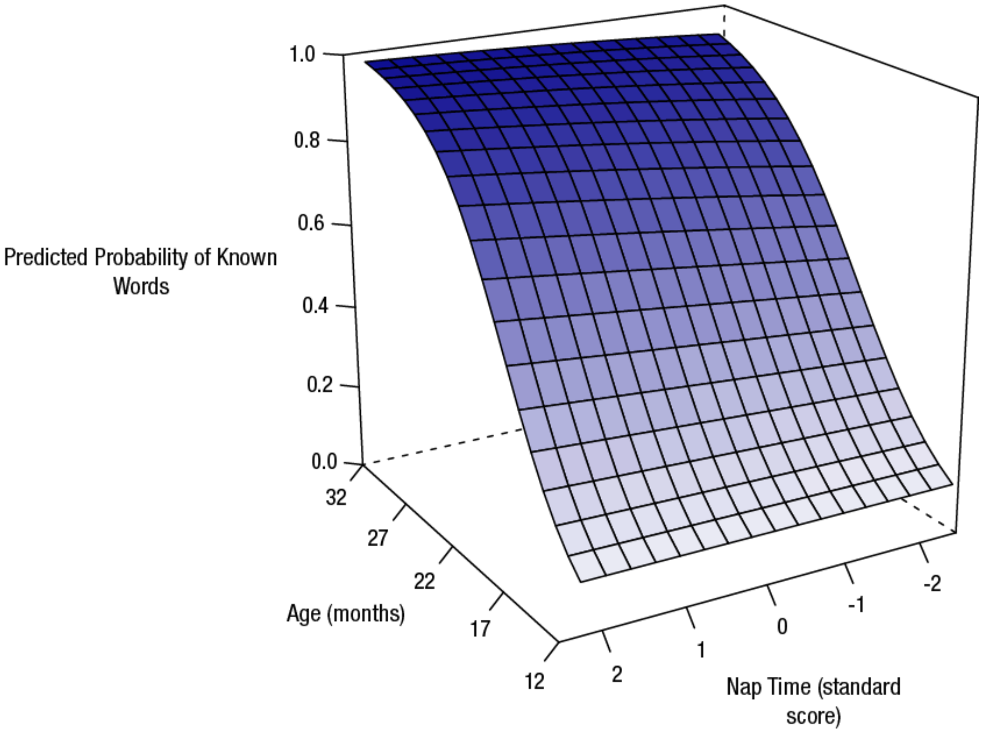

Figure 6.1. The effect of nap time on receptive vocabulary development with age. Standard scores are displayed for nap time. Children with longer daytime naps show a faster rate of receptive vocabulary development with age.

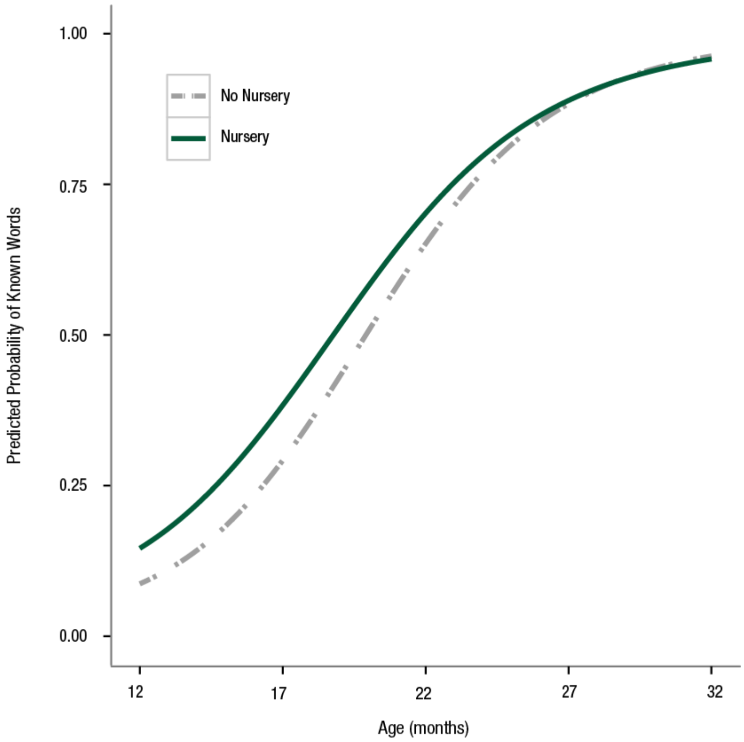

Figure 6.2. Receptive vocabulary development in children who attend nursery and who are not in day care. Nursery attendance had a significant effect on the initial status and the rate of change as well.

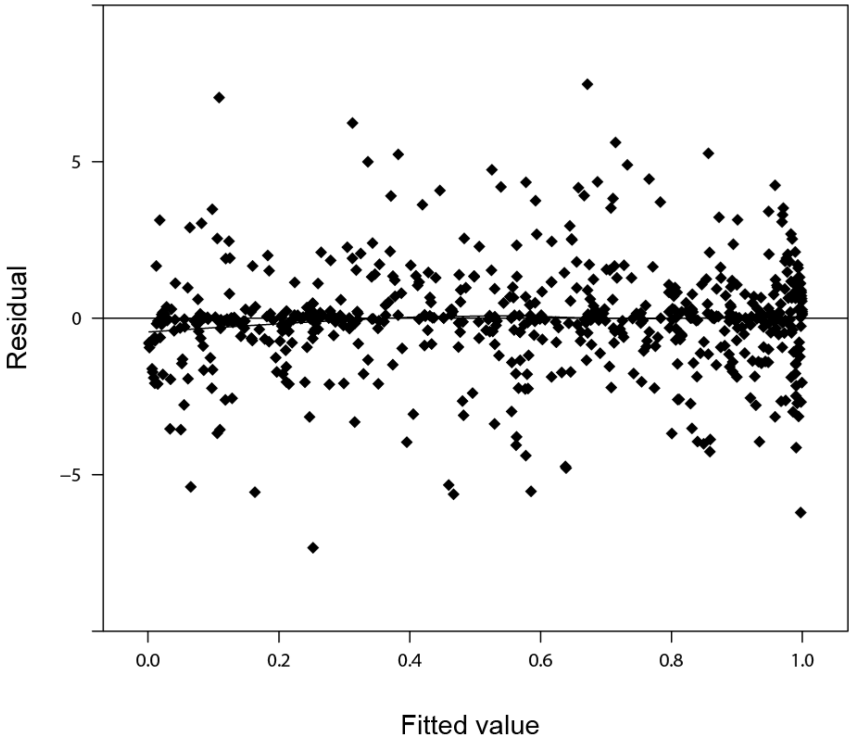

Figure 6.3. Residual plot for OCDI comprehension score.

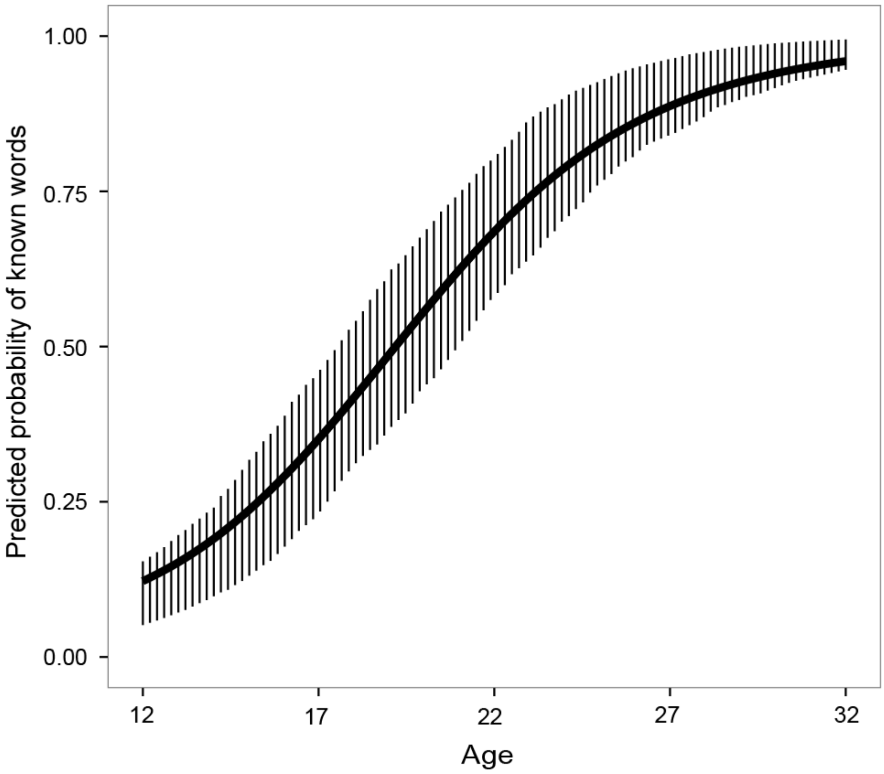

Figure 6.4. Model predicted values for OCDI comprehension score by age. Confidence intervals are shown.

For production, the effect of nap time and sex had a significant impact on the rate of vocabulary growth: longer daytime naps resulted in enhanced growth of expressive vocabularies. The effect of night-time sleep approached significance: children who slept longer at night tended to have slower rates of growth. Although not significant, the effects of nap time and breastfeeding on initial status contributed to a significantly better model fit, and so were kept in the model. Somewhat unsurprisingly, both receptive and expressive vocabularies of girls developed at a faster pace than boys' (Figures 6.5 and 6.6). The residual plot indicates a good model fit (Figure 6.7). Model predicted values with confidence intervals are plotted in Figure 6.8.

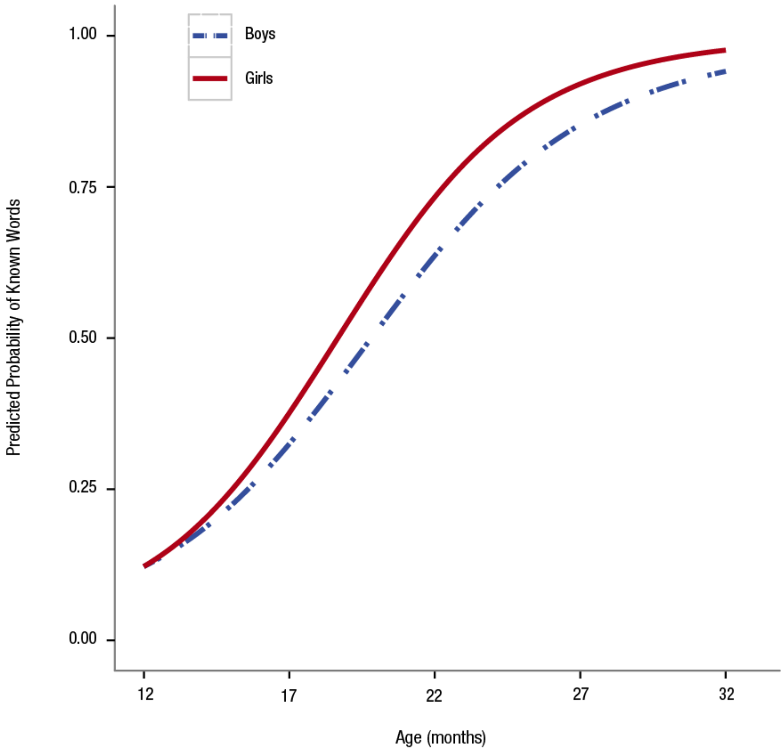

Figure 6.5. Receptive vocabulary development by sex. Girls have a faster rate of vocabulary growth.

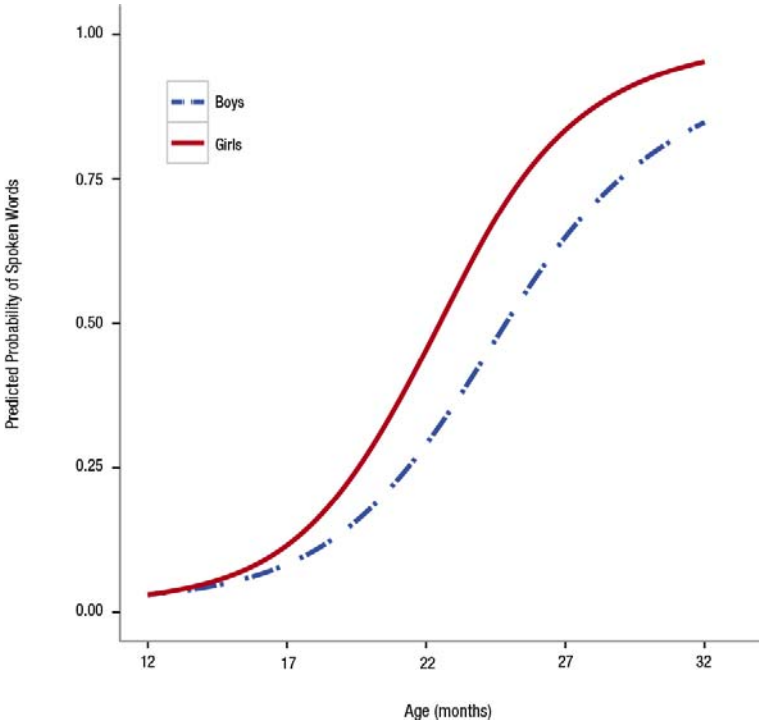

Figure 6.6. Expressive vocabulary development by sex. Girls have a faster rate of vocabulary growth.

Figure 6.1 depicts the model's representation of the relationship between receptive vocabulary size for age and nap time and highlights the finding that children with longer daytime naps show more rapid growth of receptive vocabulary. A similar relationship for expressive vocabulary scores is depicted in Figure 6.9. Moreover, there was a tendency for infants with shorter nap times to have larger productive vocabularies at the initial assessment. Figure 6.10 highlights the finding that children with shorter night time sleep master all the words on the OCDI at younger ages.

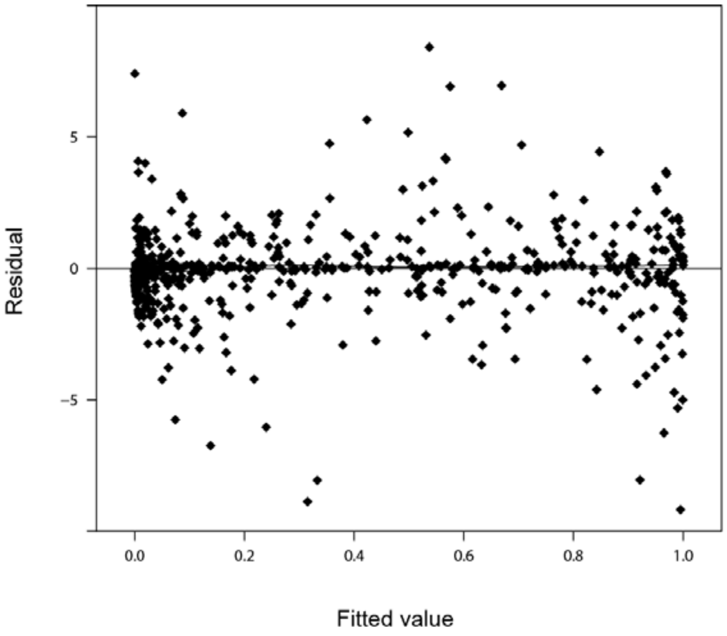

Figure 6.7. Residual plot for OCDI production score.

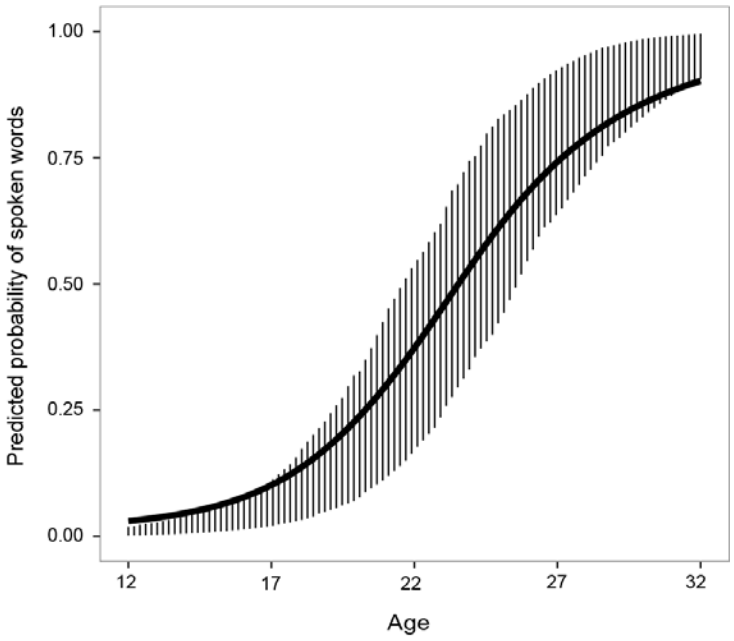

Figure 6.8. Model predicted values for OCDI production score by age. Confidence intervals are shown.

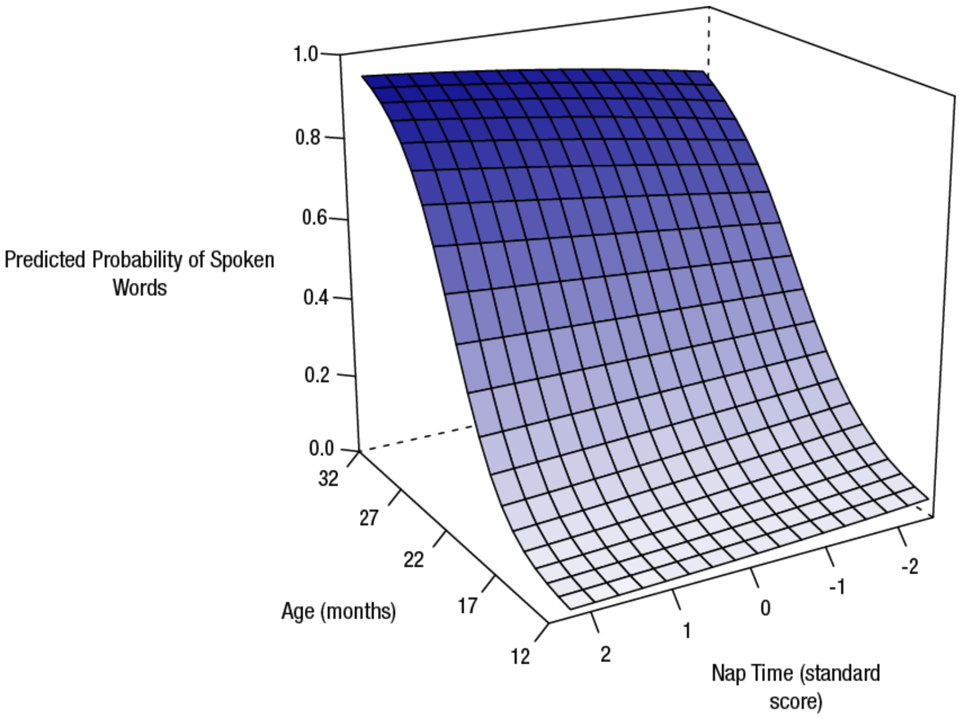

Figure 6.9. The effect of nap time on expressive vocabulary development with age. Standard scores are displayed for nap time. Children with longer daytime naps show a faster rate of expressive vocabulary development with age.

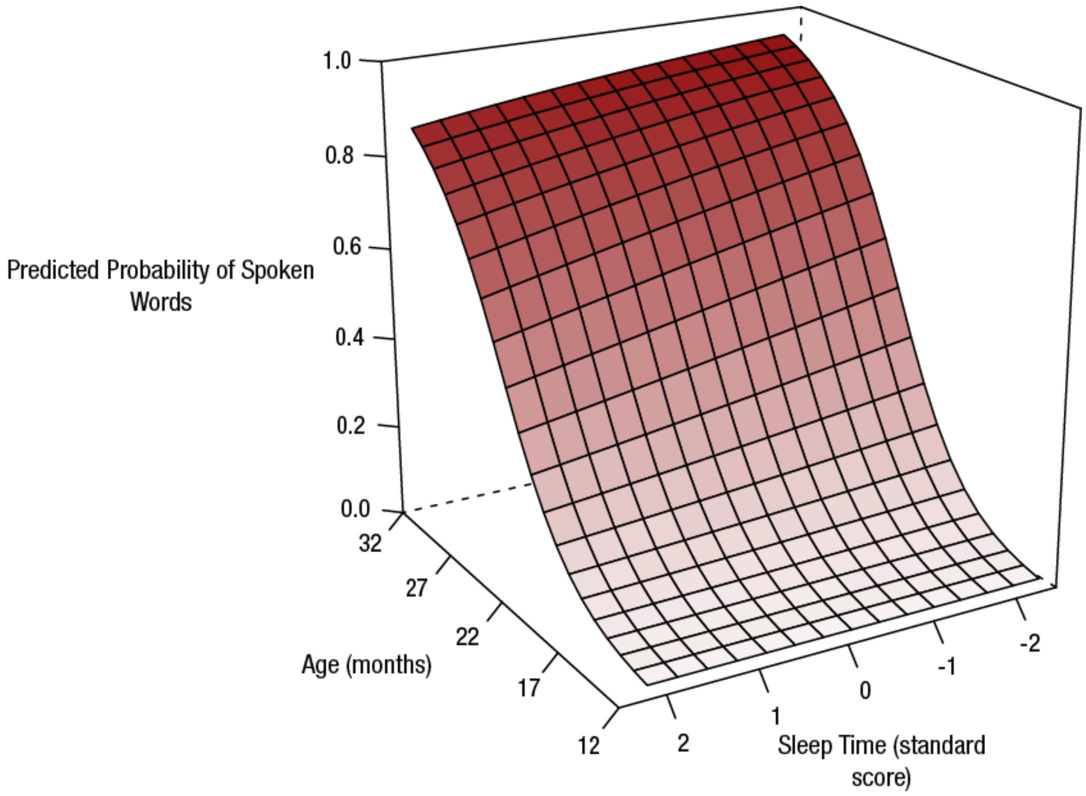

Figure 6.10. The effect of sleep time on expressive vocabulary development with age. Standard scores are displayed for sleep time. Children with longer night-time sleep show a slower rate of expressive vocabulary development with age.

Table 6.3. *Mixed-effect model parameters for OCDI Comprehension score*

		Unconditional means model					Unconditional growth model					Final model				
		parameter	Lower CI	Upper CI	Z	p	parameter	Lower CI	Upper CI	Z	p	parameter	Lower CI	Upper CI	Z	p
Fixed effects																
Initial status	Intercept	-0.14	-0.59	0.34	-0.6	.55	-2.47	-2.67	-2.26	-23.97	<.001	-2.93	-3.29	-2.58	-16.2	<.001
	Nursery attendance											0.69	0.25	1.12	3.1	.002
	Breastfeeding (ref: formula fed)											0.03	-0.1	0.17	0.45	>.250
Rate of change	Age						0.34	0.31	0.36	33.8	<.001	0.34	0.3	0.38	17.57	<.001
	Nap time											0.01	0	0.03	1.99	.047
	Nursery attendance											-0.04	-0.08	0	-1.93	.054
	Sex (ref: male)											0.05	0.02	0.08	3.61	<.001
Random effects		Variance	SD				Variance	SD				Variance	SD			
	Intercept	8.99	3				2.2	1.48				2.09	1.45			
	Age	0.15	0.39				0.02	0.14				0.02	0.14			

Notes. CI – 95% confidence interval, SD – standard deviation.

Table 6.4. *Model comparisons for OCDI Comprehension*

	Df	AIC	BIC	logLik	deviance	Chisq Chi	Df	p
Unconditional means model	4	8482.7	8500.7	-4237.3	8474.7			
Unconditional growth model	5	8063.5	8085.9	-4026.7	8053.5	421.21	1	<.001
Final model	10	7470.7	7514.9	-3725.4	7450.7	561.83	5	<.001

Notes. Df- degrees of freedom, AIC – Akaike Information Criterion, BIC – Bayesian Information Criterion, logLik – log likelihood.

Table 6.5. *Mixed-effect model parameters for OCDI Production score*

		Unconditional means model					Unconditional growth model					Final model				
		parameter	Lower CI	Upper CI	Z	p	parameter	Lower CI	Upper CI	Z	p	parameter	Lower CI	Upper CI	Z	p
Fixed effects																
Initial status	Intercept	-0.81	-1.4	-0.21	-2.66	.008	-5.56	-5.91	-5.21	-31	<.001	-5.57	-5.94	-5.2	-29.42	<.001
	Nap time											-0.33	-0.7	0.04	-1.75	.079
	Breastfeeding (ref: formula fed)											0.12	-0.08	0.31	1.19	.233
Rate of change	Age						0.47	0.44	0.5	30.2	<.001	0.43	0.39	0.46	23.1	<.001
	Nap time											0.04	0	0.07	2.25	.025
	Sleep time											-0.02	-0.04	0	-1.93	.053
	Sex (ref: male)											0.09	0.06	0.13	5.24	<.001
Random effects		Variance	SD				Variance	SD				Variance	SD			
	Intercept	34.18	5.85				6.91	2.63				6.99	2.64			
	Age	0.3	0.55				0.05	0.22				0.05	0.22			

Notes. CI – 95% confidence interval, SD – standard deviation.

Table 6.6. *Model comparisons for OCDI Production*

	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	p
Unconditional means model	4	7921.1	7921.1	-3947.6	7895.1			
Unconditional growth model	5	7524.9	7524.9	-3746.2	7492.4	402.72	1	<.001
Final model	10	6947.2	6991.4	-3463.6	6927.2	516.86	5	<.001

Notes. Df- degrees of freedom, AIC – Akaike Information Criterion, BIC – Bayesian Information Criterion, logLik – log likelihood.

Discussion

In the present study, our aim was to investigate how individual differences in day and night-time sleep contribute to vocabulary development. After an initial sleep and vocabulary assessment, we followed vocabulary development in infants and toddlers over a period of 6 months. This design permitted us to model the vocabulary development of each child and study the extent to which the measured sleep variables explain individual differences between children. We found that longer daytime naps were positively associated with the rate of both expressive and receptive vocabulary development. Interestingly, those children who had longer nap times, had smaller expressive vocabularies at 12 month of age. In addition, those who slept less during the night exhibited a larger rate of expressive vocabulary growth. Perhaps unsurprisingly, the statistical growth curve analysis revealed that girls develop more quickly in terms of their vocabulary size. Furthermore, attending nursery or day care had a positive effect on the initial vocabulary status but a negative effect on the rate of receptive vocabulary growth across the cohort of 246 children. Children who do not attend day care start to develop at later ages but catch up around their second year of life.

The positive association between daytime sleep and vocabulary development may seem unsurprising in the light of Friedrich et al. (2015) and our results described in Chapters 3 and 4—which showed that a daytime nap helps to consolidate new word forms and facilitates the generalisation of novel word meanings—though it should be noted that these studies failed to report a correlation between the *length* of the nap and increments in word learning, reported in the current study. Furthermore, studies with 15 month olds (Hupbach et al., 2009) and pre-schoolers (Kurdziel et al., 2013) found that after a nap children retain the information they had learnt for at least 24 hours, in contrast with children who did not have a nap after learning. One interpretation of this pattern of findings is that as a result of the infant's memory system—

especially the hippocampal short term stores—having a smaller capacity and probably being more prone to interference, more frequent naps are needed to efficiently consolidate new information (Kurdziel et al., 2013). This interpretation seems to be further supported by the finding that the performance of non-habitual nappers decayed less during wakefulness than that of habitual nappers (Kurdziel et al., 2013). On the other hand, Gomez and Edgin (2015) argue that for infants younger than 18 months old, sleep-dependent memory consolidation cannot be the consequence of hippocampal replay during sleep due to the immaturity of hippocampal circuits; though it might reflect sleep-dependent consolidation of cortical learning, perhaps through synaptic descaling (Tononi & Cirelli, 2014).

In contrast to daytime naps, the finding that night-time sleep was negatively associated with expressive vocabulary size may seem somewhat counter-intuitive. However, similar results have been found in younger infants' general cognitive development. In neonates, the longest sleep period was negatively associated with later cognitive outcome (Anders, Keener & Kraemer, 1985; Freudigman & Thoman, 1993). A similar relationship was found in premature infants at 36 weeks of gestational age (Gertner et al., 2002). Infants who slept more over 24 hours and slept more during the night (within a 12 hour period) had a lower index of mental development at 6 months. These findings may be explained with shorter sleep duration as a sign of a more mature sleep pattern (Anders et al., 1985; Gertner et al., 2002). Alternatively, the increased duration of the longest sleep period may reflect a higher stress reactivity, thus a greater vulnerability, which may be associated with less than optimal cognitive development (Freudigman & Thoman, 1993).

It is important to note that our results are not consistent with the only comparable study in similar age groups. Dionne et al. (2011) found no relationship between night time-sleep and vocabulary outcome at 18 and 30 months (though there was a positive correlation between night-time sleep at 18 months and vocabulary at 60 months) and reported a negative association between daytime sleep at 6 months and later vocabulary score. However, there are considerable differences between the two studies. Dionne et al.'s findings are based on Spearman correlations, and therefore offer no control for confounding factors. Nevertheless, the authors provide information from structural equation modelling with the appropriate control for other variables, but only for the measure of sleep-wake consolidation. Although it is not straightforward to compare, the negative association between sleep-wake consolidation and vocabulary outcome still suggests a contrasting set of results to that of the present study. Our methodology provides more accurate measures of sleep, as we used sleep diaries for a minimum 7 days permitting parents to indicate sleep times with an accuracy down to 15 minute intervals. Furthermore, Dionne et al. (2011) used interviews with rounded hours as pre-set answers for questions, making it difficult to investigate subtler individual differences. Moreover, we defined the total night-time sleep as the difference between the sleep duration and the time spent awake during the night. One major advantage of Dionne et al.'s study is their sample size of 1029, although it is important to note that the sample consisted of twins. Furthermore, they carried out the sleep assessment at fixed ages of: 6, 18 and 30 months, whereas we studied children from a wider age range.

We also found sex and nursery school attendance to be significant predictors. The faster vocabulary development of girls is well-known from the literature (Mayor & Plunkett, 2011; Westerlund & Lagerberg, 2008), thus, our results are convergent. Less is known about the effects of attending pre-school on vocabulary development. Intriguingly, those infants who attend day care develop more rapidly in terms of their vocabulary size but infants who did not seem to reach the same level by the age of two. A negative effect was reported on the vocabulary of 5 year old children in day care (Feinstein, Robertson & Symons, 1999), but positive effects on cognitive development were also found (see Waldfogel, Han & Brooks-Gunn, 2002). However, as highlighted in the review of Waldfogel et al. (2002), maternal education and socio-economic status may modify this association. Since our sample is homogeneous in this regard, it is hard to make generalisations to more heterogeneous samples.

One major limitation of our study is that our sample was homogeneous in terms of maternal education, placing a limit on how much our findings can be generalised. Furthermore, we conducted the sleep assessment at only one instance and the age of the assessment varied across children. However, the multilevel statistical modelling we employed is able to handle this type of sampling, provided sufficient data points are collected for each participant. With this in mind, following both sleep and vocabulary development longitudinally could provide important further insights into their relationship. Furthermore, even though sleep diaries have been shown to be fairly accurate (Kaplan et al., 2012; Werner et al., 2008), they cannot provide data as accurate as physiological measures. This is especially true for measuring the number and the time of awakenings, as parents are often not aware of their children waking up during the night.

Taken together, our results shed light on some of the associations between sleep and vocabulary development. Since inconsistencies emerged in the literature, future studies are warranted to disentangle this relationship. Understanding this connection more comprehensively may allow us to identify the risk of impaired vocabulary development and allow us time to make a timely intervention.

CHAPTER 7. DISCUSSION

In the present thesis, the goal is to investigate the role of sleep in early language acquisition, specifically how napping influences word learning and generalisation of word meanings; in addition to, how vocabulary development is affected by night-time and daytime sleep. Two main approaches were employed, experimental studies and a longitudinal questionnaire-based design. In Chapter 2, the results of a preliminary study was outlined that suggested that the experimental design was appropriate to investigate word learning in pre-vocabulary spurt infants. Further to which, in Chapter 3, we combined this design, with slight adjustments, with a napping paradigm. It was shown that naps were beneficial in learning new object-label mappings. In Chapter 4, this finding was extended to the generalisation of word meanings. Our results indicated that only those infants who slept after learning were able to generalise the meaning of a word. Chapter 5 provides data on the sleep patterns of children aged 6-32 months from the Oxfordshire area. It was demonstrated that our newly developed sleep diary is a valuable tool in investigating infants' and toddlers' sleep patterns. Furthermore, the disruptive effect of the nursery on sleep was also brought to the fore. In Chapter 6, the longitudinal associations between vocabulary development and sleep were investigated, with the outcome that longer nap time predicted a faster pace of both expressive and receptive vocabulary growth. However, shorter sleep time was associated with a more rapid expressive vocabulary growth. In sum, our findings indicate that there are several processes in language acquisition that are related to sleep, especially to daytime naps in infancy and toddlerhood.

In this chapter, we discuss our findings in relation to the existing literature and elaborate on the extent to which our hypotheses were confirmed in light of all the studies outlined in this doctoral thesis. First, the discussion will focus on whether the associations between sleep and word learning, generalisation and vocabulary development in infancy have been more established with the contribution of our results. Following which, a summary of both the theoretical and practical implications of the research will be provided. Finally, some of the limitations of the presented studies and findings will be reflected on in order to outline suggestions for further research.

Overview of main findings

Word learning and sleep

One of the study's main goals was to show that napping facilitates word learning in infants. The hypothesis for the research was based on memory and word learning literature conducted on adults, children and infants. In adults, numerous studies have shown the beneficial role of sleep in consolidating different types of memories (Diekelmann & Born, 2010; Rasch & Born, 2013; Walker, 2012; Walker & Stickgold, 2010). Results are similar in children (Backhaus et al., 2008; Kurdziel et al., 2013; Wilhelm, Prehn-Kristensen, et al., 2012), particularly for declarative memories. However, the facilitating effect of sleep on procedural memories is more controversial (Wilhelm, Prehn-Kristensen, et al., 2012). The single study that was carried out in declarative memory consolidation in infants also found similar results. After a nap, 6 and 12 month olds had better recall of the target actions in a deferred imitation task. Moreover, those infants' performance who napped after training was still better 24 hours later, suggesting a long-term impact (Seehagen et al., 2015). Similarly, word learning and their integration into the mental lexicon both benefit from sleep. There are a series of studies investigating the role of sleep in integrating newly learnt words to the mental lexicon in adults (Dumay & Gaskell, 2007, 2012; Tamminen & Gaskell, 2013; Tamminen et al., 2010; Tham et al., 2015) highlighting that sleep does not just strengthen memories but it also helps in their reorganisation. Data on children suggest a similar relationship. Recall and integration of newly acquired words was demonstrably better after sleep for school-aged children (Ashworth et al., 2014; Brown et al., 2012; Henderson et al., 2015; Henderson et al., 2012). For declarative memories, the sleep group had a better performance than the wake group, which was due to the wake group's decline in performance (Henderson et al., 2012). In 6-9 month old infants, a nap also provided protection against forgetting of newly learnt words in an ERP study. The increased N200-500 component in the correct pairing condition indicated a transfer to long-term memory store. However, as there was no observable effect in the N400 component, the integration of the words into the existing semantic network is questionable (Friedrich et al., 2015). In sum, most of the studies reported some form of sleep-dependent consolidation, although only one experiment carried out on those in their infancy. As a result of which, we aimed to provide confirmation of these results through a different methodology.

The study described in Chapter 3, addressing the word learning-sleep issue, supported our hypothesis. We demonstrated that infants significantly increased target preference after a nap for newly learnt object-label pairs, whereas the performance of the wake group did not change systematically. Infants were tested in familiar word trials in both sessions and showed positive naming effects without any group difference, indicating they understood the task and both the nap and the wake group had similar levels of alertness. Our outcome suggests that the novel word-object associations were consolidated during sleep. However, our experiment in Chapter 4–although investigating word learning was not its main aim–resulted in controversial findings. Specifically, the naming effect did not differ significantly from zero in either of the conditions or sessions. In addition, there was no change in the naming effect between sessions in either of the groups. Nevertheless, because the two groups did not differ, we think that the lack of target preference was the consequence of the decreased attention levels and the non-participation in the task, most possibly due to the length of the experiment.

Another factor which makes the interpretation less straightforward is the negative naming effect observed after training in the nap group. As we proposed in Chapter 3, our most likely explanation is that the neural networks became saturated due to tiredness, which led to a mismatch preference. In our designs, the nap group was necessarily more tired because they were asked to come in just before their normal nap time in order to maximise the likelihood of sleeping in the laboratory. However, two factors undermine the generalisability of this effect. First, there was no group difference in this regard. Second, we did not observe similar results in Chapter 4. Hence, further studies are needed to decide whether the negative naming effect is replicable and, if so, why it happens.

In addition to the sleep-word learning association, we investigated the possible effects of vocabulary size on the sleep-dependent consolidation of newly learnt word forms. Our hypothesis stating a positive association between expressive vocabulary and the consolidation of words was based on the study of Henderson et al. (2015). The authors showed that in children, higher expressive vocabulary size was associated with the sleep-dependent benefits in lexical integration and phonological memory, similar to the positive correlation we observed between expressive vocabulary and the performance improvement after sleep (Chapter 3). The explanation provided for these findings being that sleep has a possible role in the fine tuning of pre-motor and motor representations. As an analogy to bird studies, we proposed that infants whose motor control and vocabulary production were less developed were less able to benefit from sleep due to less established sensorimotor integration (Margoliash & Schmidt, 2010; Tse et al., 2007; Wilhelm, Prehn-Kristensen, et al., 2012).

However, our experiments did not provide answers to other interesting theoretical questions. It remains unclear, for instance, whether the word forms became integrated into the semantic network or whether there had simply been a transfer into long-term memory. While the results of Friedrich et al. (2015) suggest the latter, Henderson et al. (2012)—although carried out on children—supports the former. Neither can we make inferences concerning the memory systems involved in word learning and consolidation. Henderson et al. (2012) showed a different pattern in the consolidation of declarative memories and in the recall of novel words.

Our results also suggest that after sleep there is an improvement in performance, as opposed to a lack of forgetting—further supporting the argument that word learning system is different from the declarative memory system. What makes comparing findings for different age groups even more complicated is that the memory systems involved might change with age. For example, Gomez and Edgin (2015) suggest that in infants younger than 18 months only cortical learning is possible due to the immaturity of the hippocampus. More experimental and neuroimaging work is needed in order to address these questions.

Generalisation and sleep

Our second main goal was to show that sleep is needed to generalise word meanings in infancy, as this is a process requiring memory reorganisation. In adults, it has been shown that various tasks demanding the restructuring of existing knowledge—both language and non-language related—benefit from sleep (Chatburn et al., 2014; Ellenbogen et al., 2007; Fenn et al., 2003; Wagner et al., 2004). In infants, to date only four studies have investigated the relationship between generalisation and sleep. Gomez et al. (2006) and Hupbach et al. (2009) showed that 15 month olds generalised the knowledge of a predicting relationship between word strings using the preferential listening task. In addition, word meanings were also generalised in 9-16 month olds after sleep—this being suggested by the decreased N400 component of the ERPs in the correct category pairing trials compared to incorrect category pairings (Friedrich et al., 2015). However, in 2.5 year olds, wakefulness, not sleep, appeared to enhance generalisation (Werchan & Gomez, 2014). It is unclear whether the different findings resulted from the different methodology and designs used or from the older age of the subjects. Given the fact that these existing findings were inconclusive, the aim of the research carried out in this study was to further disentangle the generalisation-sleep relationship in infancy.

Moreover, additional evidence that sleep helps to generalise novel word meanings in infancy was provided in the study outlined in Chapter 4 in which infants were tested on objects which were similar in shape but different in colour to the training objects. In this way, infants were able to generalise the word meaning after one exemplar of a category. The observed association suggests that sleep does not passively consolidate memories, but rather that it does so as an active process—referred as 'memory evolution' by Stickgold and Walker (2013). With this, irrelevant information is being forgotten and the key features of the category are retained.

Nevertheless, our study does not answer the question of whether the lack of sleep dependent generalisation in Werchan and Gomez (2014) is a consequence of a developmental trajectory. Gomez and Edgin (2015) argue that before approximately 18 months of age, the beneficial effects of sleep is either due to cortical consolidation or the promotion of forgetting. In older toddlers, after the maturation of the hippocampal structures, the sleep-dependent replay of memories in the hippocampus facilitates learning. While the hippocampus is able to associate new information in a few exposures, cortical learning is a slower process. It is plausible that this developmental shift is reflected by the studies which found that younger infants were incapable of remembering new information after only a few exposures (Gomez & Edgin, 2015). The authors hypothesise that in the different stages of memory development a different mechanism underlies sleep-dependent memory consolidation. While the beneficial effect of sleep in cortical learning can be explained with the synaptic homeostasis hypothesis, the active system consolidation hypothesis describes better the hippocampal learning process (Gomez & Edgin, 2015). Our results showed that both learning object-label associations and generalisation benefit from sleep in 16 month olds. Under Gomez and Edgin's framework this would mean that both processes are independent of hippocampal function. However, our studies did not provide evidence of which memory system was responsible for learning, nor of the underlying physiological mechanisms.

Vocabulary development

The third main goal was to investigate the longitudinal relationship between sleep and vocabulary development. While the existing literature, in addition to Chapters 3 and 4, provides evidence using experimental designs that sleep and naps have an enhancing role in learning, whether it has a longitudinal effect has been less investigated. Ednick et al. (2009) review studies in which some kinds of sleep measure predicted mental outcome at later ages. However, language as outcome has received less scrutiny. Available data suggest that circadian sleep regulation and the proportion of night-time to daytime sleep has been associated with vocabulary development (Bernier et al., 2010; Dearing et al., 2001; Dionne et al., 2011). We intended to investigate further these associations, concentrating on individual differences.

Our study revealed that longer daytime naps were positively related to the rate of both expressive and receptive vocabulary growth. Interestingly, shorter night-time sleep duration was associated with larger expressive vocabulary development. The positive effects of napping are in line with the results of a number of experimental studies (Friedrich et al., 2015; Gomez et al., 2006; Hupbach et al., 2009; Kurdziel et al., 2013; Seehagen et al., 2015) in addition to ours, as described in Chapters 3 and 4. However, the negative effects of night-time sleep is somewhat counter-intuitive. In younger infants it was shown that shorter night-time sleep was the predictor of more advanced mental development (Anders et al., 1985; Freudigman & Thoman, 1993; Gertner et al., 2002); an association which may be the result of a more mature neural system (Anders et al., 1985; Gertner et al., 2002). Others proposed that longer sleep duration may be the consequence of higher stress reactivity and greater vulnerability (Freudigman & Thoman, 1993).

Nonetheless, some inconsistency emerged in the literature as a result of findings. For example, Dionne et al. (2011) reported no relationship between night-time sleep and vocabulary development and found a negative association between daytime sleep in 6 month olds and vocabulary outcome. Given that there are significant differences in the study designs and the statistical analysis used, direct comparison presents a number of problems. Hence, further research on the topic is warranted, with systematic investigation of different age groups—and preferably, with the addition of longitudinal examination of sleep patterns.

Implications

In the light of the research summarised above, some theoretical and practical implications should be considered.

Our findings not only extend our knowledge of sleep-dependent memory consolidation to infancy, but they highlight the importance of daytime napping for this age group. Infants in our experiments described in Chapters 3 and 4 only showed learning after a nap, indicating that a nap can induce dramatic changes in consolidation. In addition, the duration of daytime naps was associated with faster vocabulary development (Chapter 6). Importantly, previous research showed that if infants and pre-schoolers did not have a nap soon after learning, night-time sleep was not able to restore or evoke the same consolidation effects (Hupbach et al., 2009; Kurdziel et al., 2013; Seehagen et al., 2015). However, there was a difference in habitual nappers and non-nappers in this regard. Only the performance of habitual nappers improved after the daytime nap (Kurdziel et al., 2013), implying maturational changes. Furthermore, the number and the duration of daytime naps decrease significantly during the first few years of life (see Chapter 5 and Iglowstein et al., 2003), suggesting that with maturation naps lose their importance. Taking all these results together, napping is clearly crucial for learning in early development, however, it is still unclear why.

The most plausible explanation is that infants' less mature memory system makes them dependent on frequent daytime naps due to its lower capacity. More specifically, this could be the result of two factors. First, infants' short term storage capacity may be smaller, thus preventing saturation and interference—with more frequent sleep periods needed to empty these stores. Second, consolidation may be slower or less efficient during wake. While adults and older children are able to preserve memories for a longer time, either because they can consolidate some of the memories during wake or they have a larger storage capacity which does not become full that quickly. Gomez and Edgin (2015) might provide some explanation for the underlying mechanisms. They hypothesised that because of the immaturity of the trisynaptic circuits of the hippocampus, hippocampal replay is not present in infants younger than 18-24 months. They also proposed that before that age infants acquire information through cortical learning. It is possible that due to the extensive use of the cortical learning process, synaptic downscaling is required more often to preserve the learning capacity of the synapses as proposed in the SHY model (Tononi & Cirelli, 2014). Taken together, while the importance of napping in infancy is well-established in the literature, the exact underlying neurophysiology is far from being fully understood.

Beyond theoretical interests, our research along with previous findings on napping in infancy, clearly has practical relevance. While studies have not been carried out on the longitudinal consequences of daytime sleep restriction, our longitudinal vocabulary development study, together with experimental results, suggest that it may seriously affect cognitive functioning, particularly in habitual nappers. Therefore, nurseries and parents should be advised not to sacrifice daytime sleep in favour of increasing activities; additional activities which parents and nurseries incorrectly believe will enhance cognitive development. Of course, it does not mean that daytime naps should be forced on those whose neural system is mature enough to work optimally without daytime sleeping. Identifying methods which could assess the need for daytime naps would be advantageous to distinguish between those who does not require daytime sleeping and those who have a potential sleep problem.

Limitations and future research

The limitations of each study has been discussed previously. Having said that, our aim here is to summarise some of the general points and make suggestions for future research.

One of the major factors which hinders the generalisability of our research is the homogeneous sample from whom we collected data. Our participants came from the geographical area of Oxfordshire which has a fairly homogeneous socio-economic background, as indicated by the high number of years parents spent in education. Research has shown that socio-economic status has an impact on language and vocabulary development (Hoff, 2003; Hoff & Tian, 2005). Therefore, further research is needed to decide whether our conclusions can be generalised to and considered legitimate for children of lower socio-economic status.

Circadian effects on cognition have not been investigated in infancy, though on the basis of adult literature it can be conjectured that they may influence learning (Escribano & Diaz-Morales, 2014; Sherman, Mumford & Schnyer, 2015). Although we did not find a significant difference in time of the day between the nap and no-nap groups in our experiments, nap infants were inherently at different phase of their circadian cycle as they were brought in to the laboratory before their usual nap time. By contrast, the no-nap group was brought in after their usual nap time. It is not clear how the interplay of process S and C (i.e. sleep-wake homeostasis and circadian rhythm, respectively) are different in infants of adults. Thus, in addition to circadian processes influencing cognitive functioning to some extent, the basic physiological mechanisms of the infant's circadian rhythm also needs to be investigated.

Another important issue which places a limit on how firm are our conclusions is the quality of the data. This is probably the most significant challenge not just of this thesis but the field itself. Infants are not aware of the purpose of the experiments and most likely they do not have an understanding of the testing situation. Furthermore, there are many factors affecting their cognitive processes which they are not able to control, such as hunger, fatigue, boredom and many other possible variables that researchers may be not aware of and infants are not able to explain. Moreover, infants' shorter attention span requires shorter test sessions and can easily lead to high numbers of invalid trials and substantial dropouts. All these influencing factors lead to a high variability of the data in the experiments, which poses a challenge for the most widely accepted statistical methods. Limited number of participants and trials together with high variability in the data result in less statistical power. To account for some of the variance caused by inter-individual differences, we used statistical methods such as repeated measures ANOVA (Chapters 2, 3 and 4) and random effects modelling (Chapter 6). These methods also provide some control for the error arising from multiple testing. For the same reason, we used difference scores which provide a control for object preference and a measure for the effect of labelling. This way, we were also able to reduce the number of comparisons. Taken together, although we made efforts to control for Type I statistical errors, our statistical approach was not conservative due to our concern about losing statistical power. One way to overcome the aforementioned problem is to replicate research findings. Unfortunately, we were unable to reproduce the results of Chapter 3 in Chapter 4. It is hard to know whether this was because of the unreliability of the data or the slight changes in the research design. Therefore, our conclusions should be treated with the necessary cautions.

Another important theoretical and practical question is whether night-time sleep could restore the lack of daytime napping. Given that we did not repeat our assessments the day after the initial learning and testing, our studies did not provide information on this. However, previous experimental results suggest that if shortly after learning a period of sleep does not follow, sleep-dependent performance gains are not present, even following a later period of sleep (Hupbach et al., 2009; Kurdziel et al., 2013; Seehagen et al., 2015). As Kurdziel et al. (2013) found, there is an important difference between habitual and non-habitual nappers, thus further research should look into the topic of the longitudinal relationship between daytime naps and learning in both groups.

We proposed that the need for daytime naps has its basis in infants' less efficient consolidation of stimuli. While this explanation seems feasible, more targeted research is warranted to directly test this hypothesis. Moreover, supporting evidence on the neurophysiological level should underpin this interpretation. Polysomnographic examinations and imaging techniques might provide relevant information.

Conclusions

Despite its limitations, we believe the present thesis broadens our understanding for infants' sleep and its relation to cognitive development. Showing that a daytime nap enhances word learning and generalisation in 16 month olds and the positive association between the length of daytime naps and vocabulary development, we have contributed significantly to gaining an understanding of sleep-dependent memory processes in infancy. Furthermore, our results highlight the importance of daytime naps in early childhood, which in addition to its theoretical significance has an unquestionable practical relevance.

ABBREVIATIONS

2-AFC	Two-alternative forced choice
AIC	Akaike Information Criterion
ANCOVA	Analysis of covariance
ASC	Active system consolidation hypothesis
BIC	Bayesian Information Criterion
CLS	Complementary learning systems
CVC	Consonant-vowel-consonant
D	Distracter
df	Degrees of freedom
EEG	Electroencephalographic
fMRI	Functional magnetic resonance imaging
IPL	Intermodal preferential looking
LDP	Long term depotentiation
logLik	Log likelihood
LTP	Long term potentiation
M	Mean
NREM	Non-rapid eye movement
OCDI	Oxford Communicative Development Inventory
REM	Rapid eye movement
SD	Standard deviation
SHY	Synaptic homeostasis hypothesis
SNORI	Sleep and Naps Oxford Research Inventory
SWA	Slow wave activity
SWS	Slow wave sleep
T	Target
TFT	Thin film transistor

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APPENDICES

Appendix 1.

Mixed-effect model parameters for the full model of OCDI Comprehension score

		parameter	SE	Z	p
Fixed effects					
Initial status	Intercept	-2.91	0.21	-13.65	< .001
	Nap time	-0.05	0.11	-0.42	.672
	Sleep time	-0.07	0.12	-0.58	.560
	Time spent awake	0.05	0.01	0.45	.654
	Nursery attendance	0.65	0.23	2.85	.004
	Sex (ref: male)	0.03	0.21	-0.13	.901
	Breastfeeding (ref: formula fed)	0.09	0.16	0.54	.587
Rate of change	Age	0.34	0.02	15.91	< .001
	Nap time	0.02	0.01	1.70	.089
	Sleep time	0.00	0.01	0.05	.963
	Time spent awake	-0.01	0.01	-0.45	.653
	Nursery attendance	-0.04	0.02	-1.78	.075
	Sex (ref: male)	0.05	0.02	2.62	.009
	Breastfeeding (ref: formula fed)	0.00	0.02	0.00	.997
Random effects		Variance	SD		
	Intercept	2.08	1.44		
	Age	0.02	0.14		

Notes. CI – 95% confidence interval, SD – standard deviation.

Model comparisons of the final and the full model of OCDI Comprehension

	Df	AIC	BIC	logLik	deviance	Chisq Chi	Df	p
Final model	10	7470.7	7514.9	-3725.4	7450.7	561.83	5	<.001
Full model	17	7483.1	7558.2	-3724.5	7449.1	1.67	7	.976

Notes. Df – degrees of freedom, AIC – Akaike Information Criterion, BIC – Bayesian Information Criterion, logLik – log likelihood.

Appendix 2.

Mixed-effect model parameters for the full model of OCDI Production score

		parameter	SE	Z	p
Fixed effects					
Initial status	Intercept	-5.90	0.37	-15.87	< .001
	Nap time	-0.33	0.19	-1.71	0.09
	Sleep time	-0.02	0.21	-0.09	.926
	Time spent awake	0.13	0.19	0.69	.491
	Nursery attendance	0.33	0.40	0.83	.406
	Sex (ref: male)	0.26	0.37	0.69	.492
	Breastfeeding (ref: formula fed)	0.07	0.28	0.23	.816
Rate of change	Age	0.44	0.03	13.30	< .001
	Nap time	0.03	0.02	2.10	.036
	Sleep time	-0.12	0.02	-0.93	.351
	Time spent awake	-0.02	0.02	-0.92	.357
	Nursery attendance	-0.01	0.03	-0.24	.809
	Sex (ref: male)	0.07	0.03	2.32	.021
	Breastfeeding (ref: formula fed)	0.01	0.03	0.34	.738
Random effects		Variance	SD		
	Intercept	6.84	2.62		
	Age	0.05	0.22		

Notes. CI – 95% confidence interval, SD – standard deviation.

Model comparisons of the final and the full model of OCDI Production

	Df	AIC	BIC	logLik	deviance	Chisq Chi	Df	p
Final model	10	6947.2	6991.4	-3463.6	6927.2			
Full model	17	6957.8	7032.9	-3461.9	6923.8	3.46	7	.840

Notes. Df – degrees of freedom, AIC – Akaike Information Criterion, BIC – Bayesian Information Criterion, logLik – log likelihood.