Exploring the interplay of sleep, memory and development in infancy:
A holistic perspective on vocabulary learning

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Abstract

This PhD thesis by articles investigates the associations between sleep, memory processes, motor skill, and vocabulary growth in infancy. The underlying theoretical framework on child development is holistic; It conceptualises vocabulary learning as related to memory and as resulting from the interaction between the body and the environment. The goal is to provide a biologically grounded understanding of how phonological and lexical networks are built. The first article reviews research on the associations between sleep and word learning during infancy. In 16 identified papers, positive associations between sleep and several aspects of word learning are revealed. Moreover, the studies show associations between the sleeping brain activity and word learning, long-term effects of infant sleeping habits on vocabulary development and relationships between the child's existing knowledge and the consolidation of linguistic information post-sleep. The second article further examines the role of sleep in language development by focusing on word form generalisation, showing that the combination of a post-encoding nap with nocturnal sleep significantly supports it. These findings clarify the relative importance of naps and nighttime sleep for phonological development. The third article investigates the associations between the evolution of sleep patterns, motor skills progression and vocabulary growth over the first two years. It shows nonlinear associations among these domains, emphasising their emergence at ages of sharp developmental change. This study highlights the necessity of adopting a dynamic systems perspective to comprehend vocabulary growth as the product of continuous interactions between cognition, the body, and the environment. Together, these articles illuminate early lexical development by examining it in relation to memory processes and its connections with motor development. They highlight that the developmental changes observed in the domains of communication, locomotion and sleep regulation are mutually intertwined and rely on shared memory processes and on interactions between the child and their surroundings.

Author’s declaration

I declare that this thesis is a presentation of original work and I am the lead author in every article included. Prof. Marilyn Vihman and Prof. Tamar Keren-Portnoy, my PhD supervisors, are co-authors of the articles (for specific contributions, please read the Research Degree Thesis Statement of Authorship document at the beginning of each article). This work has not been previously presented for a degree or other qualification at this University or elsewhere. All sources are acknowledged as references.

Some of the material included in Paper 2 was included in talks presented at the International Congress of Infant Studies (Ottawa, July 2022), the WRDTP 11th Annual Conference (Sheffield, June 2022) and the HRC Doctoral Fellowship Competition (York, June 2022). The abstract of Paper 2 has been submitted to the International Congress for the Study of Child Language (Prague, 2023). Some of the material in Paper 3 was included in poster presentations at the Building Linguistic Systems Conference (York, June, 2022) and the WRDTP 11th Annual Conference (Sheffield, June 2022). The abstract of Paper 3 has been submitted to the International Congress for the Study of Child Language (Prague, 2023). Paper 1 has been published (Full reference: Belia, M., Keren-Portnoy, T., & Vihman, M. (2023). Systematic review of the effects of sleep on memory and word learning in infancy. Language Learning, 73(2), 613-651). Paper 3 has been submitted for publication (under review).

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> “This is a story of how a Baggins had an adventure, and found himself doing and saying things altogether unexpected.”
>
> J. R. R. Tolkien, The Hobbit, pp. 5.

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General introduction

The emergence of a communication system in humans is a long-standing puzzle in human research, since the times of ancient philosophy. This system, characterised by the articulation of complex sound patterns associated with multifaceted meanings, fundamentally defines us as humans. In contemporary psycholinguistic research a central question is how this communication system is represented in our minds. Researchers address this question by investigating the nature of linguistic representations. But how do these representations form, and how are they integrated in the mind? And crucially, how does this process look when representations are first being laid down, during development? This PhD thesis actively engages in the ongoing debate surrounding these questions, with a specific focus on vocabulary acquisition during infancy. The primary objective is to contribute to the development of a biologically sound model for understanding vocabulary growth, one that considers how learning actually happens at the physiological level.

Learning as an embodied and unconscious process

Essentially, language learning is the process underlying the formation and modification of linguistic representations; what we conceptualise on an abstract level as representations are essentially neural associations spanning different areas of the brain. So, learning happens through changes in the connections between different clusters of neurons. These associations are built through experience; neural associations are formed as a group of neurons collectively re-activates in response to re-experiencing similar situations, making behavioural responses more effective (see Mayford et al., 2012). At its core, then, learning involves the potentiation and modification of synaptic connections in the course of our daily interactions with the environment (Mayford et al., 2012). Human interaction with the environment primarily occurs through motor activity, especially self-generated locomotion. Locomotion allows us to navigate to different locations, experience diverse environments, and direct our bodies toward specific objects and areas of interest. These activities foster exploration, elevating the likelihood of encountering novel as well as familiar situations. This, in turn, enriches our synaptic networks by forging new connections between novel and familiar experiences, thereby promoting generalisation and synaptic plasticity.

It is no accident that Campos and colleagues named their influential paper on the effects of crawling onset on vocabulary in infancy ‘Travel broadens the mind’: the title aptly captures the effects of self-initiated locomotion on cognition (Campos et al., 2000). Traditionally, research has studied cognition from a symbolic perspective, often isolating the cognitive domain from the body in which it is embedded. This approach tends to downplay the influence of the environment on cognition (Smith, 2005). Such de-contextualisation poses the risk of overlooking important insights into how learning happens, even within traditionally cognitive domains, such as language. Conversely, adopting an embodied perspective on cognition acknowledges that cognitive knowledge emerges through exploration of and interaction with the environment, in concert with the brain’s learning mechanisms, outlined in the past paragraph. This approach is likely to offer a more realistic and comprehensive account of how language learning takes place.

The paragraphs above have outlined how our brains are wired online through experience. A substantial body of evidence indicates that much of the consolidation and modification of synaptic connections also takes place offline, particularly during sleep (see Rasch & Born, 2013, for a review). Over the past few decades several theories have been proposed to explain this. Some recognise an active role of the electrophysiological activity of the sleeping brain in reactivating synaptic networks associated with wake experiences, consolidating memories for these experiences (Wilson & McNaughton, 1994; Lee & Wilson, 2002). One such theory is Active System Consolidation (ASC), which builds on the Complementary Learning Systems (CLS) model (McClelland, McNaughton, & O'Reilly, 1995). CLS emphasises the interaction of two memory systems, the neocortex and the hippocampus, in learning and memory. The neocortex stores structured long-term knowledge, while the hippocampus rapidly encodes and links cortical patterns associated with real-time experiences into short-term memory traces. ASC posits that, during sleep, memory traces are jointly reactivated in both the hippocampus and neocortex, facilitating their redistribution and consolidation in long-term knowledge networks (Born & Wilhelm, 2012; Gais & Born, 2004; Mölle et al., 2002). Other theories acknowledge a more indirect role of sleep in the consolidation and reorganisation of synaptic connections. For example, the Synaptic Homeostasis Hypothesis (SHY) proposes that synaptic circuits are strengthened during wakefulness, and sleep serves to regress synapse weights to baseline level, preparing the network for new learning in subsequent wake periods (Tononi & Cirelli, 2003; Vyazovskiy et al., 2008). After this process, memories which were strongly encoded during wakefulness have a better chance of surviving the downscaling process (Tononi & Cirelli, 2003; Vyazovskiy et al., 2008).

What is consistent across these different accounts is the unanimous support for the role of sleep in mediating synaptic connections and associations across memories. Given that language learning inherently involves associative processes, such as associating word forms with meanings, concepts within the same category, and similar speech signals (e.g., phones) within the same sound category (e.g., phonemes), the role of sleep in language learning becomes plausible. Accordingly, numerous studies run with adults and school-aged children support the idea that sleep aids in the consolidation of linguistic memories. In particular, sleep supports recall of new word forms (e.g., Gais et al., 2006), their integration into the existing mental lexicon (Dumay & Gaskell, 2007; Tamminen & Gaskell, 2008), learning of new word-meaning associations (e.g., Henderson et al., 2012; Brown et al., 2012), generalisation of new phonological categories across different acoustic patterns (Fenn et al., 2003) and learning of artificial grammar (Nieuwenhuis et al., 2013). Neuroimaging studies further strengthen the link between sleep and language learning by revealing positive associations between EEG signals related to memory consolidation during sleep and the integration of newly learned words into the mental lexicon (Tamminen et al., 2010; Tamminen et al., 2013). Furthermore, cued recall studies show that cueing newly learned words during sleep promotes memory reactivation and enhances the integration of the new words into the mental lexicon (Tamminen et al., 2017). This phenomenon extends beyond linguistic memories, as demonstrated by studies associating new information with an odour during encoding and then cuing that information with the same odour during sleep to enhance memory consolidation (Rasch et al., 2007). Davis and Gaskell (2009) provide a theoretical framework for understanding sleep-related consolidation in word learning. Extending the ACS and CLS models to the lexical domain, they suggest that the hippocampus initially encodes a sparse individual memory representation during initial exposure to a new word. Subsequently, during sleep, these sparsely encoded memories are replayed and redistributed into the existing lexical network in neocortical long-term memory. During speech perception, we observe lexical competition of the newly learned words with similar sounding lexical entries. This suggests that the new entries have been fully embedded into the mental lexicon and that accessing them has become automatic (Davis & Gaskell, 2009). These findings are noteworthy as they suggest that the learning of linguistic material follows routes similar to those involved in learning in any other domain. This makes a compelling case for the processes leading to linguistic representations being inherently intertwined with memory and learning processes. Accordingly, models of vocabulary development should integrate linguistic theories with frameworks pertaining to how memory consolidation works. However, current investigations in language acquisition within the developmental domain infrequently incorporate insights from memory and learning studies.

The proposed research adopts a holistic perspective on vocabulary development, integrating both online and offline aspects of memory and learning. By integrating an embodied understanding of cognition and incorporating contemporary knowledge regarding the role of sleep in memory and learning, this thesis aims to provide a more comprehensive and biologically-grounded explanation of word learning during infancy.

Why a holistic perspective on vocabulary learning in infancy?

Infancy is marked by significant changes in self-initiated locomotion, language acquisition, and sleep patterns, making it particularly relevant to examine vocabulary development through the multidimensional lens proposed in this thesis.

In the motor domain, infancy is typically characterised by the emergence of the gross motor skills involved in the onset of self-initiated locomotion, an event described as the “psychological birth of the human infant” (Mahler et al., 1975, cited in Campos et al., 2000). This symbolism is not arbitrary; crawling and walking represent significant milestones, as they signal infants’ autonomy in directing their attention, interest, and body movements towards objects in their environment. These developmental events mark a significant shift in the child's life, representing their first move towards independence from their caregiver. No longer reliant on being carried, infants can now voluntarily focus on and engage with objects in their surroundings in novel ways and from different angles. This has profound implications for several aspects of cognition, such as visual proprioception, memory and spatial cognition (see Anderson et al., 2013, for a review). Moreover, the onset of independent locomotion brings about profound changes in infants' interactions with others and significantly impacts their socio-emotional worlds, inevitably influencing the development of language. Crawling infants' interactions become richer, with increased distal communication, more numerous and diverse referents and interlocutors (Campos et al., 2000). Independent walking further enhances communicative abilities, as infants can carry objects, engage further in distal communication, and elicit more linguistic input from caregivers (Clearfield, 2011; Karasik et al., 2014). The link between locomotion and language development is validated by studies showing cascading effects of locomotion attainment on vocabulary outcomes. For example, independent walkers exhibit increased receptive and productive vocabulary (Walle & Campos, 2014), spend more time interacting with caregivers, and vocalise more compared to their peers using walkers (Clearfield, 2011).

Infancy is also marked by unique sleep patterns that undergo significant changes in later childhood, adolescence and adulthood. Total sleep duration over a 24-hour period decreases gradually, from around 20 hours in newborns to 13 hours in the second half of the first year and 12 hours in toddlerhood (Galland et al., 2012). Perhaps the most notable feature of infant sleep is its polyphasic nature, characterised by sleep occurring in multiple bouts throughout the day (i.e., naps), as well as during the night, particularly at the younger ages. This is due to the absence of a circadian rhythm at birth. Circadian rhythm starts to emerge only around 2-3 months of age, as infants become increasingly responsive to such environmental cues like the light-dark cycle (Sheldon, 2002). As children develop, the number of night awakenings and daytime naps reduces (Galland et al., 2012; Staton et al., 2020; Tham et al., 2017). The relationship between a child's typical napping behaviour, nocturnal sleep and learning is debated. Napping is prominent in infant sleep, prompting researchers to explore its potentially unique role in infant memory consolidation. Some propose that children transition out of napping when cognitive resources allow them to retain information until bedtime, consolidating it during sleep (Riggins & Spencer, 2020). This aligns with studies showing the extended developmental trajectory of the hippocampus (Jabès & Nelson, 2015), which approaches full maturation around 2 years after birth (Gao et al., 2009). In this view, habitual nappers might benefit more from sleeping shortly after learning episodes, avoiding potential interference accumulated during wakefulness (Esterline & Gómez, 2021; Kurdziel et al., 2013; Riggins & Spencer, 2020). However, studies show that a post-encoding nap continues to enhance memory consolidation not only in preschoolers (Werchan et al., 2021) but also in adults (Tamminen et al., 2017). These findings pose a challenge to the notion that the benefits of napping on memory are tied to infancy, as older children, with more mature memory systems and no habitual napping, still exhibit positive effects. This suggests that the precise roles of naps and nocturnal sleep in memory consolidation remain uncertain. Inconsistencies in longitudinal studies examining the effects of early sleep patterns on later vocabulary outcomes further highlight the complexity of the role of sleep and naps in language acquisition and the need to investigate it further (Horváth and Plunkett, 2016; Dionne et al., 2011; Knowland et al., 2022).

Finally, the first two years of life witness the emergence of the first lexical networks. As mentioned at the outset, how humans learn to speak has always intrigued researchers and parents alike. The complexity of human language historically led to a theory that poses the innateness of linguistic knowledge (Chomsky, 1957). However, this raises questions about where this innate knowledge might derive from genetically, how it is encoded and how it is specified in the brain (Thelen & Smith, 1994). Furthermore, infants and adults are undeniably different: In childhood we see increasing complexity in every aspect of behaviour (at the macroscopic level) and, at the same time, dramatic inter-individual variability in developmental trajectories. But if linguistic knowledge is innate, why do we witness variability and, most importantly, how do we account for learning? Nativist and constructivist views propose the existence of conceptual constraints (i.e., constraints not dependent on perception or action) that guide development through ordered and universal stages (see Thelen & Smith, 1994, for a review). However, questions arise about the encoding of these constraints, how they might be "built-in" into our brains, and how they could explain changes and, crucially, discontinuities and inter-individual variability in development.

In contrast, the Dynamic Systems Theory (DST) of development, originally proposed by Thelen and Smith (1994), adopts a biologically-grounded perspective on development. The central idea of DST is that infant development does not require innate or internally constructed laws; instead, it is generated through the infant’s own activity. This activity is fuelled by the complexity of our organism, a system embedding multiple domains in constant communication with one another and the environment (Smith & Thelen, 2003). A representative example is crawling behaviour. According to DST, crawling emerges as the most efficient solution currently available to a problem posed by the environment, like moving across the room to reach an object or person of interest for interaction. Infants with sufficient neuromuscular strength and coordination to support a hands-and-knees posture will crawl to achieve this goal. As they grow in strength and balance, walking upright replaces crawling, as walking is generally a more efficient way for humans to move around a flat, regular surface. In turn, walking allows infants to look forward, gaining a wider angle to scan the environment. In addition, it frees up their hands for further exploration, object manipulation, and the achievement of multiple goals simultaneously, such as interacting while manipulating the object or bringing objects of interest to caregivers (Smith & Thelen, 2003; Karasik et al., 2014). Thus, a crucial aspect of DST is the constant interaction, across different domains, of real-time task requirements, the environment, and behaviour. In this framework action, vision, cognition, and learning are part of a unified system. Changes in one domain cause changes in other domains and this happens in continuous interaction with the environment, as the individual is constantly embedded in their surroundings.

The proposed work aligns with DST in the objective to provide a biologically sound explanation for infant development. My work focuses on vocabulary development. DST's theoretical framework allows us to contextualise the word learning process within a theory in which cognition, sleep regulation, and the motor domain interact and, through these interactions, influence vocabulary development as well as each other. Through this framework, my study will address the following questions: What does vocabulary learning look like in developing humans? How is it influenced by the ongoing changes in the sensorimotor domain? What is the role of sleep in vocabulary learning and what aspects of the learning involved in lexical development does sleep support?

The thesis reports three studies conducted to address these questions:

- Paper 1: A systematic review surveying existing evidence on the influence of sleep on word learning in children under three years of age. The goal of the review was to assess how research on early word learning has been conducted in relation to evidence regarding the impact of sleep on memory and learning. Additionally, the review examines longitudinal studies investigating the influence of changes in sleep habits on lexical development during infancy. The review also addresses two less explored aspects: the role of existing knowledge in sleep-dependent memory consolidation and the effects of electrophysiological activity in the sleeping infant brain on subsequent memory performance.
- Paper 2: An experiment conducted with 8-month-old infants to determine whether a nap immediately following auditory exposure to words spoken by one talker enhances infants' recognition of the same word forms produced by a different talker (i.e., word form generalisation). This study bridges an important gap in the research about the relative role of naps and nocturnal sleep on early word learning by studying their role on phonological learning across different acoustic contexts (i.e., different human voices). Phonological learning is frequently overlooked in research about word learning. However, prior to a child’s ability to associate words and their meanings and use language referentially they must first encode and access the phonological forms of words and recognise them in running speech (Vihman, 2017). The findings from this study make a substantial contribution to our understanding of phonological learning by highlighting the significant role of daytime naps in this process.
- Paper 3: A longitudinal investigation following the development of sleep patterns, vocabulary, and self-initiated locomotion in children at 7, 12, 16, and 24 months of age. Clear developmental changes occur during this period, including the progressive shift towards prevalent nocturnal sleep, the onset of

self-locomotion and the emergence of first lexical comprehension and production. Previous research has linked evolving sleep patterns and cognitive development and has crucially tied self-initiated locomotion to changes in vocabulary within this period. Also, recent studies have connected the emergence of self-locomotion to changes in infant sleep patterns. Collectively, this evidence reveals a complex interplay between sleep patterns, motor skill advance, and language growth. The study integrates these three domains, which had previously been studied independently, to illuminate the interconnected dynamics among them throughout the initial two years of life and offer novel insights into how early vocabulary emerges from dynamic developmental changes spanning multiple dimensions. The findings from this study show nonlinear associations between the three domains, emerging at ages of marked developmental change.

In the “General discussion and Conclusions” chapter I provide a comprehensive summary of the findings of the three studies and outline potential directions for future research that have arisen from these investigations but remain unexplored. I then discuss how my findings contribute to a biologically grounded understanding of phonological and lexical development in infancy. I conceptualise these processes as holistic phenomena emerging from the combination of linguistic input, multisensory feedback, self-regulation and memory processes, and proprioceptive feedback from the child’s own vocalisations and physical actions.

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Abstract

This systematic review surveyed research on the associations between sleep and the memory processes involved in word learning in infancy. We found only 16 studies that addressed this topic directly, identifying associations between infant sleep and the memory processes, the identification of word forms in running speech, and the stabilisation and generalisation of new word form–meaning associations. Some studies investigated changes in brain responses after word learning and in sleep parameters during post-learning sleep. Others investigated the long-term effects of sleeping patterns on later vocabulary development. All but one of these studies identified positive associations between sleep and word learning in early childhood, extending similar findings from studies on adults and school-aged children. However, there remain several gaps in the current research on early lexical development and sleep. Future investigations should address these gaps for researchers to better understand lexical development and to create links between memory and language acquisition research.

Introduction

Linguistic representations inherently derive from memory and learning processes. For researchers to propose sound accounts of language development, they must integrate linguistic theories with accounts of knowledge formation and processing (Menn et al., 2013). However, what research has revealed about memory and learning has seldom been invoked in relation to how infants learn the phonological forms and meanings of new words. Here, we have reviewed studies that have addressed aspects of infant word learning within the specific framework of sleep and memory research. Given the well-established role of sleep in learning and memory, we believed that a systematic review comprehensively addressing which characteristics of sleep have been found to influence infant learning of word forms and meanings would add important insights to understanding of lexical development, from the acquisition of individual words and categories to the formation and growth of lexical networks. Moreover, a review of the methods and the variables that have been reported in the literature so far should help to guide future research agendas.

Background Literature

We begin by describing two aspects of sleep-associated memory consolidation, namely, stabilisation and enhancement, and how they are evidenced in development. We then summarise the neurological mechanisms underlying sleep-associated memory benefits and the ways that brain development might be linked to naps in infancy.

The role of sleep in learning and memory

Through consolidation, newly encoded memories undergo stabilisation and enhancement. Stabilisation is the maintenance and/or strengthening, in memory, of the specific items that were learned, or in other words, veridical memory of new material retained over a delay (Stickgold & Walker, 2013). Besides being stabilised, new representations go beyond retention when they are embedded into knowledge networks (Landmann et al., 2014; Walker & Stickgold, 2006). This is referred to as memory enhancement, evidenced by item integration or multi-item generalisation (Stickgold & Walker, 2013).

Item integration is the assimilation of the memory into a network of existing related memories (see Lewis & Durrant, 2011). Multi-item generalisation is the formation of a network based on the implicit extraction of regularities across multiple new memories; new experiences matching those regularities are integrated into the network, which then changes to accommodate them. Thus, lexical categories can be seen as memory networks with respect both to their content and to their creation.

During development, sleep has been found to support memory stabilisation in several domains such as in the recall of actions (e.g., Seehagen et al., 2015), in picture recognition (e.g., Giganti et al., 2014), and in face recognition (e.g., Horváth et al., 2018). Infant memory enhancement is also supported by sleep through gist extraction and generalisation. For example, in Konrad et al.'s (2016) study, infants were shown actions by using three different but similar puppets. Only infants who napped afterward recalled the actions shown with a fourth puppet that was similar to those employed in the demonstration. Thus, sleep supported the extraction of the shared features across multiple puppets (i.e., gist extraction). The infants' ability to replicate the actions with previously unseen puppets indicated that they could disregard the differences between the original and new puppets and recognize the new puppets as members of the target-action-performing puppet category. Similar sleep effects have been investigated for the extraction of the core structure of continuous stimuli. In two studies, one by Gómez et al. (2006) and one by Hupbach et al. (2009), 15-month-olds were familiarised, through listening, with continuous nonword strings that followed an underlying structure. The infants who remained awake after exposure to the strings preferred to listen to those that they had heard during familiarisation, but infants who napped developed a preference for whichever type of string was first presented at testing, familiar or novel. This was interpreted as evidence that the nap group generalised the string structure following sleep: They noticed structural dependencies in the first test trial and preferentially attended to those structures for the rest of the test.

The electrophysiological activity of the sleeping brain has been theorised to be responsible for memory consolidation (but see Yonelinas et al., 2019). Specifically, new memories stabilise and integrate into memory networks through their replay during sleep, a process that involves the hippocampus and the neocortex and that is driven by sleep spindles (i.e., neural oscillations generated during sleep) during slow-wave sleep (see Gais & Born, 2004). Memory replay also strengthens commonalities across existing and new memories, thereby contributing to memory integration and multi-item generalisation (Lewis & Durrant, 2011). Several studies have reported a relationship between electrophysiological activity during sleep and subsequent memory performance (e.g., Rasch et al., 2007); evidence of these associations in children and infants have been sparse but compelling (Kurdziel et al., 2013, 2018; Seehagen et al., 2019). Alternatively, sleep has been theorised to lower all the synaptic connections to a baseline level, thereby indirectly supporting memory: The synapses that were highly active in wakefulness (i.e., those activated by the specific experience or referent encountered and their connections to existing knowledge networks) would be the strongest after sleep (Tononi & Cirelli, 2003, 2006; Vyazovskiy et al., 2008). This process could again explain both memory stabilisation and enhancement (Landmann et al., 2014; Lewis & Durrant, 2011). Because of the prolonged maturation of the hippocampus, this model has been proposed to better represent infant memory consolidation than does the spindle-driven consolidation account that assumes a key role for the hippocampus (Gómez, 2017; Gómez & Edgin, 2015, 2016).

The prolonged maturation of memory networks has also been hypothesised to be directly associated with polyphasic sleep (i.e., multiple bouts of sleep in a day) in early childhood. Specifically, newly formed memories in a less mature brain may be more prone to interference and forgetting and thus benefit from repeated consolidation through naps (Mullally & Maguire, 2014; Riggins & Spencer, 2020). In this view, abandoning daytime naps and transitioning to exclusive nocturnal sleep (i.e., sleep consolidation; Dionne et al., 2011) may be associated with brain maturation (Lam et al., 2011). Observations of toddlers who do or do not continue to nap habitually have supported this hypothesis. In Esterline and Gómez's (2021) study, 4-year-olds who had ceased taking habitual naps remembered new word–meaning associations regardless of whether they napped or not after training, whereas habitual nappers who remained awake between learning and testing did not show retention of the words. In Kurdziel et al.'s (2013) study, spatial memories decayed over 5 hours spent awake in 3- to 5-year-old habitual nappers but not in nonhabitual nappers. Thus, letting go of naps might indicate a better capacity for retaining new information over prolonged wakefulness. Furthermore, among those who napped, only habitual nappers showed postnap memory improvements while nonhabitual nappers showed no change. So, it is possible that the naps of habitual nappers lead to more efficient consolidation than do those of nonhabitual nappers.

Long-term positive associations have also been found between early sleep consolidation and multiple aspects of cognition at later ages, with more mature sleeping patterns in the preschool years predicting mental development scores (Dearing et al., 2001), executive function abilities (Bernier et al., 2010), and academic achievement at school entry (Bernier et al., 2021). However, naps have also been found to be essential to early memory consolidation. Kurdziel et al. (2018) found that emotional memories in 34- to 64-month-olds were not consolidated immediately after a post-learning nap but only after nighttime sleep following learning, with the greatest memory improvements found in toddlers who had napped immediately after learning the previous day, suggesting that timely sleep might be as important at this older age as it is in early infancy, especially in combination with nocturnal sleep (Hupbach et al., 2009; Seehagen et al., 2015). In the next sections, we review how memory consolidation is associated with different aspects of word learning and the variables that have been found to mediate this relationship. We then discuss which aspects need to be addressed in infancy and introduce the present work.

The case of language development

Processes of memory stabilisation and enhancement apply to several aspects of word learning. Preserved and/or increased recognition for or recall of the form–meaning associations learned before sleep indicates memory stabilisation (e.g., van Rijn et al., 2020). For example, 7- to 12-year-olds in Henderson et al.’s (2012) study recalled novel word form–meaning associations only after sleep. In Brown et al.’s (2012) study, although 7-year-olds recognized the phonological form of newly learned words even 3 to 4 hours after learning, without sleeping, they showed improved recall in a cued task after a 24 hour delay that included sleep. This suggested that, although under certain circumstances new phonological forms might be recognised even without sleep, sleep nevertheless supports recall.

Memory enhancement in adults and children has been observed in the form of memory integration of new phonological forms (i.e., lexicalization; Gaskell & Dumay, 2003). Just as memory integration is the assimilation of new item memories into existing networks, lexicalization is the assimilation of a new word form into the network of phonologically related known words (Dumay & Gaskell, 2007). The subsequent reorganisation of the phono-lexical network is evidenced when the form of the new word starts competing with similar sounding known words, slowing their identification and recognition (Dumay & Gaskell, 2007). This indicates that the new phonological form is engaged in the network as lexical activity spreads. In both adults (Dumay & Gaskell, 2007) and school-aged children (Brown et al., 2012; Henderson et al., 2012, 2015), this phenomenon has been observable not immediately after exposure to the new word form but only after a delay that included sleep. The importance of sleep for lexicalization is supported by positive associations between spindle activity during post-learning sleep and competition effects between a new word form and its neighbours in subsequent wake time (e.g., Tamminen et al., 2010).

Lexicalization has also been found to be mediated by the richness of phono-lexical networks. For example, James et al. (2019) observed that the phonological similarity of a novel word to known words was advantageous for immediate recall of a novel word form in both adults and 7- to 9-year-olds, demonstrating that similarities between the to-be-learned information and existing knowledge support learning (McClelland, 2013; Tse et al., 2007). However, post-sleep recall was stronger in children than in adults and for novel words without neighbours than for words with phonological neighbours, suggesting that sleep-dependent memory stabilisation may be modulated by the richness of existing knowledge. In addition, vocabulary level predicted recall and recognition of the novel word forms in both adults and children. Henderson et al. (2015) observed similar associations, as children with better expressive vocabularies recalled the word forms better after overnight sleep.

Implications for infancy

Compared to adults and older children, infants spend a long time asleep and also exhibit remarkably rapid advances in language development. Therefore, investigating whether the observed associations between sleep and word learning hold for early development is crucial. Central to this investigation is understanding which memory mechanisms underlie early word learning as well as their neurophysiological basis as expressed in associations between postsleep memory benefits and electrophysiological activity during sleep following learning. As we outlined above, daytime napping has generally been positively associated with infant memory performance. However, the consolidation of uninterrupted overnight sleep and the transition away from daytime napping are also fundamental aspects of development with long-term implications. Therefore, investigating whether such longitudinal effects of sleep consolidation on infant cognition also exist in the language domain would add to researchers' understanding of vocabulary development as a continuous learning and memory process.

Some of the research that we described above showed that the integration of new words into the lexicon is mediated by the strength and connectivity of existing lexical networks. This phenomenon has received less attention in younger children. Nevertheless, the influence of prior phonological and lexical knowledge on early word learning has been observed both globally as a positive effect of vocabulary size on new word learning (e.g., Torkildsen et al., 2008) and locally in infants' increased facility in acquiring novel words that contain sounds that appear consistently in their vocalisations (Vihman, 2022), better short-term memory for nonwords containing often-produced sounds (Keren-Portnoy et al., 2010), and the predictive power of consonant production consistency in the emergence of first word use (Majorano et al., 2014; McCune & Vihman, 2001; McGillion et al., 2017). The relevance of an individual child's prior knowledge fits well with dynamic and usage-based views of development (Pierrehumbert, 2003; Thelen & Smith, 1994). However, few studies have so far systematically considered this in relation to sleep in early development.

Formulating age-appropriate research questions and methods is essential in infant studies. Infant research methods must, by definition, adapt to emergent cognitive and physical abilities and attention and memory capacities. Therefore, infant research has traditionally employed an array of experimental methods, each designed to test infants of designated age ranges. Also, different methods tap different aspects of word learning. As we will show in this review, studies investigating sleep effects on infant word learning have examined different age groups with a wide array of methods, limiting cross-study comparison and generalizability. Therefore, a review of the methods and variables investigated in the literature on sleep and infant word learning should help guide future research agendas not only toward addressing existing methodological gaps but also toward conducting effective replications.

The present review

The active, beneficial (e.g., Dumay & Gaskell, 2007), and causal role (e.g., Tamminen et al., 2010) of sleep is now well-established for adult word learning; evidence has been accumulating for such effects in children (see Axelsson et al., 2016). This review aimed to synthesise and discuss developmental research about the ways that sleep supports the acquisition of new words in infancy and to verify which of the memory processes observed in adults and older children, and in nonlinguistic memories, have been identified in infant word learning. Similarly, given the dramatic changes in sleep habits during development and their effects on cognition, we examined longitudinal studies investigating these effects on lexical development. Furthermore, we reviewed findings related to two issues that remain underexplored or controversial, namely, the role of existing knowledge and the outcomes of electrophysiological activity in the infant sleeping brain on memory performance. We addressed these questions:

1. What methods have researchers employed to study the effects of sleep on infant word learning?
2. Which memory processes underlying word learning in adults and older children have researchers investigated in infants?
3. What evidence have researchers presented for longitudinal effects of sleep on infant vocabulary development?
4. What evidence is there for a role for existing knowledge in sleep-related infant consolidation of newly learned words?
5. Are there associations following word learning between electrophysiological activity in the sleeping infant brain and subsequent memory performance?

Two major reviews by Axelsson et al. (2016) and by Mason, Lokhandwala, et al. (2021) summarised several studies on related topics. Axelsson et al.’s (2016) review covered findings about sleep effects on word learning over childhood and demonstrated a key role for sleep in the consolidation of newly learned words at various ages. Mason, Lokhandwala, et al.’s (2021) review surveyed recent findings concerning the role of sleep on several cognitive domains from infancy to adolescence. Both reviews supported a direct or facilitative function of sleep on memory, learning, and brain development. They also stressed the importance of considering multiple variables such as the effects of sleep timing relative to the learning episode and nap habituality. These reviews made important contributions to researchers’ understanding of the associations between learning and sleep in development, but they either did not systematically address infancy and early childhood (Axelsson et al., 2016) or were not specifically focused on word learning and lexical development (Mason, Lokhandwala, et al., 2021). Our review has focused specifically on assessing how infant lexical development has been addressed within the framework of sleep and memory research.

We ran literature searches in December 2019 and again in November 2021. Thus, relevant publications not available in electronic databases by those dates may have remained undetected. An unavoidable bias in searching for published articles is the tendency for investigators to publish studies with positive results only. Therefore, studies finding null effects are less likely to have been published and might be missing in our review.

Methods

For the systematic review, we followed the methods outlined in Pickering and Byrne (2014), as described below.

Inclusion Criteria

Terminology

To be included, papers had to contain the keywords that we chose to address the review questions. We used the keywords to search subject headings to prevent the research from extending to less pertinent fields while also increasing the chances of including as much of the relevant literature as possible. Initially, we identified the keywords as those words used in the most often cited papers. As the search continued, we updated the list of keywords by adding synonyms and new terms (see Appendix S1 in the Supporting Information online for the final list of keywords employed in the searches).

Publication

We included only original experimental research to ensure that all the papers that we considered were primary sources and that all would have undergone a peer-review process before publication. We also consulted other kinds of publications but did not include them among those reviewed. We also searched other relevant reviews to check that we had considered all the appropriate literature to the greatest extent possible but did not include those other publications in our analysis. We imposed no limitations for the year of publication.

Sample

We reviewed studies if their samples had been selected according to these criteria:

- The children were tested between birth and 3 years of age.
- The children being tested were developing typically, that is, they had no known:
  - atypical language development,
  - atypical cognitive development,
  - neurological conditions, or
  - psychological conditions.
- The children being tested had no known specific sleep disturbances.

As our main purpose was to understand the impact of sleep on language learning in early childhood, the primary criterion was the age of the children tested. Studies where children with atypical language development were tested were excluded from the review as the unique characteristics of this population went beyond the scope of this review. Similarly, we excluded papers reporting studies of children with atypical cognitive development or neurological conditions, given the disturbances to both language development and sleep patterns often experienced by these populations. We also excluded studies where the children being tested showed conditions related to sleep, as atypical sleep patterns may impact language development in ways that exceeded the scope of this investigation.

Search Strategy and Paper Selection

We searched the literature in four databases: PsycInfo, Web of Science, Linguistics & Language Behavior Abstracts, and Scopus. These databases are all available online, and we chose them as likely to contain papers relating to our field of interest. We stored and organised the studies in a web-based reference management software tool. Once we had identified a first set of keywords through a preliminary consultation of the literature, we improved the search strings as we continued the searches. Each time that we ran a search, we evaluated the extension and relevance of its results and modified the keywords and search strings to ensure that we had browsed a sufficient range of literature without including irrelevant studies. At each round, to exclude studies that did not match all the inclusion criteria, we first screened articles on the basis of the information reported in the abstract or title. We then screened papers by reading the full text and inspected the reference list to identify additional relevant literature. Appendix S1 in the Supporting Information online provides the search strings that we employed in each database and a flow chart explaining the review process.

Results

Table 1 lists the 16 papers that we reviewed.

First author	**Year**	**Participant age (in months)**	**Title**	**Journal**
Dionne	2011	5.39 to 62.64	Associations between sleep-wake consolidation and language development in early childhood	Sleep
Friedrich	2017	6.0 to 8.0 (M = 7.2)	The sleeping infant brain anticipates development	Current Biology
Knowland	2022	6.0 to 36.0	Does the maturation of early sleep patterns predict language ability at school entry?	Journal of Child Language
Simon	2017	M = 6.21	Sleep confers a benefit for retention of statistical language learning in 6.5-month-old infants	Brain and Language

Horváth	2016	7.73 to 37.83 (initial assessment)	Frequent daytime naps predict vocabulary growth in early childhood	Journal of Child Psychology and Psychiatry
Friederich	2015	9.0 to 16.0 (M = 12.20)	Generalization of word meanings during infant sleep	Nature Communications
Friedrich	2019	14.0 to 16.0 (M = 15.12)	The reciprocal relation between sleep and memory in infancy	Developmental Science
Friedrich	2020	14.0 to 17.0 (M = 15.11)	Sleep-dependent memory consolidation in infants protects new episodic memories from existing semantic memories	Nature Communications
Horváth	2015	16.0	Napping facilitates word learning in early lexical development	Journal of Sleep Research
Horváth	2016	16.0	A daytime nap facilitates generalization of word meanings in young toddlers	Sleep
He	2020	25.1 – 29.9 (M = 26.8)	Two-year-olds consolidate verb meanings during a nap	Cognition
Werchan	2021	29.0-36.0 (M=31.43)	A daytime nap combined with night-time sleep promotes learning in toddlers	Journal of Experimental Child Psychology
Axelsson	2018	29.8	Napping and toddlers' memory for fast-mapped words	First Language
Werchan	2014	30.0 – 35.0 (M = 32.94)	Wakefulness (not sleep) promotes generalization of word learning in 2.5-year-old children	Child Development
Sandoval	2017	35.22 – 41.29 (M = 37.18)	Words to sleep on	Child Development

Williams	2014	41.26 – 43.14 (Ms)	Goodnight book	Frontiers in Psychology

Table 1. The studies included in the review (ordered by age of youngest participants).

What methods have researchers employed to study the effects of sleep on infant word learning?

In most of the studies that we reviewed, researchers employed a cross-sectional design, comparing children's memory performance after a learning task or experience following a delay during which one subgroup napped or slept and the other did not, with no experimental manipulation of sleep duration or timing. Instead, learning and testing were scheduled around each child's typical sleep times to avoid participant distress and any confounding variables (e.g., tiredness). Appendixes S2 and S3 in the Supporting Information online show the methods used in each study.

Sleep was mostly assessed via parental reports and questionnaires, often combined with other measures. In the studies by Dionne et al. (2011), Horváth and Plunkett (2016), Knowland et al. (2022), and Werchan and Gómez (2014), parental reports were the only sleep measure. Six studies also employed physiological measures, namely, polysomnography in Simon et al.'s (2017) study or actigraphy in the studies by He et al. (2020), Horváth and Plunkett (2016), Horváth et al. (2015), Horváth et al. (2016), Sandoval et al. (2017), and Werchan et al. (2021). Some studies measured sleep through physiological measures only: Specifically, the studies by Friedrich et al. (2015), Friedrich et al. (2017), and Friedrich et al. (2019, 2020) used only polysomnography, and Axelsson et al. (2018) used actigraphy. Williams and Horst (2014) included no specific measures of sleep.

Researchers used various learning and testing procedures in these studies. Simon et al. (2017) targeted word-form learning using an artificial language task. The artificial language stimuli were auditory strings of nonwords that involved no association with meaning and included no pauses or prosodic cues that could suggest word boundaries. The strings contained transitional probability cues between the nonwords. After exposure, children were tested for their ability to use such cues to detect word boundaries and retain them after a delay

In all the other studies, the tasks involved exposure to sound–meaning pairs. Of these, seven—Friedrich et al. (2015, 2017, 2019), He et al. (2020), Sandoval et al. (2017), Werchan and Gómez (2014), and Werchan et al. (2021)—involved a highly structured experimental setup in which, during learning, referents were presented visually, on a screen, while the corresponding word forms were presented auditorily (either the object label or that of the category to which the object belongs). Friedrich et al. (2020) employed a similar design but with real object–word pairings likely to be familiar to 14- to 17-month-olds, and so there was no requirement to learn new sound– meaning pairs. In four other studies—Axelsson et al. (2018), Horváth et al. (2015, 2016), and Williams and Horst (2014)—learning was embedded in a playful activity during which children received a controlled number of exposures to the novel words and referents, although Horváth et al.'s (2015, 2016) studies also included on-screen training. In two of these studies, referents were physical objects that children could manipulate while the experimenter labelled them through carrier phrases. In the other two studies, referents were represented in pictures: Axelsson et al. (2018) asked children to point to pictures; Williams and Horst's (2014) exposed children to new referents and their labels through book reading and associated activities. As the three longitudinal studies involved no experimental manipulation, they had no learning phase. Figure 1 summarises the learning procedures employed in the studies.

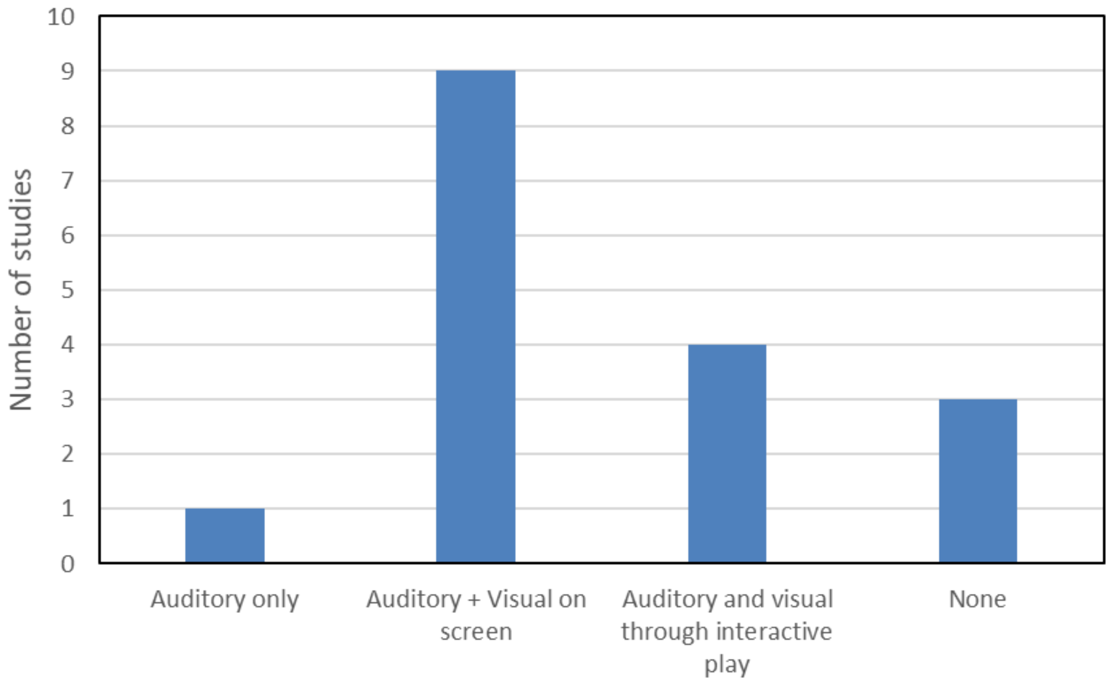

Figure 1. Learning situation.

As regards testing procedures (see Figure 2), four studies—Friedrich et al. (2015, 2017, 2019, 2020)—employed electrophysiological measures, that is, event related potential (ERP) responses to stimulus presentation and/or spindle activity during post-learning sleep, nine employed behavioural measures, and three employed surveys—Dionne et al. (2011), Horváth and Plunkett (2016), and Knowland et al. (2022). Among the behavioural studies, the measures employed were the head-turn preference procedure (Simon et al., 2017), eyetracking (He et al., 2020; Horváth et al., 2015, 2016; Werchan et al., 2021), and pointing (Axelsson et al., 2018; Sandoval et al., 2017; Werchan & Gómez, 2014; Werchan et al., 2021; Williams & Horst, 2014). The head-turn preference procedure was used with the youngest children, that is, up to 6.5 months of age. Eye-tracking was used from 16 months of age onward. Active child pointing to the object was employed in studies testing children over 2 years of age.

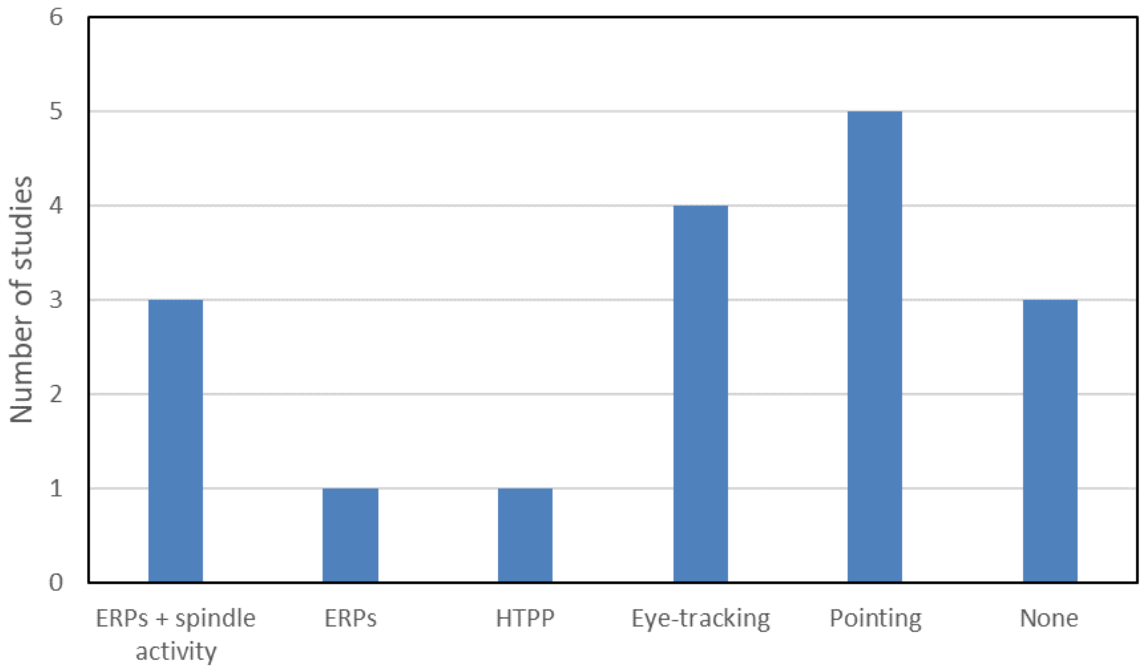

Figure 2. Testing procedures employed. ERP = event-related potential; HTTP = head-turn preference procedure.

Which memory processes underlying word learning in adults and older children have researchers investigated in infants?

Extraction of word forms from running speech.

Simon et al. (2017) examined sleep-associated extraction of the underlying distributional sound structure of language on the basis of 6.5-month-olds’ ability to identify word boundaries and segment continuous speech into individual words. They found no significant differences between the wake and nap groups’ performances. Nappers attended longer to words than to part-words (i.e., segments made up of two halves of words that had occurred sequentially in the familiarisation string) in the first block of testing and the reverse in the second block, although these differences were not significant. However, a significant interaction of testing block by trial type (i.e., words or part-words) in nappers was interpreted as evidence for the nap group’s preferring one type of word or the other, and thus as evidence for an ability of nappers to distinguish between them. Furthermore, brain activity during sleep, that is, slow-wave activity (SWA), correlated positively with the difference in looking time for words versus part-words in Block 1. Specifically, at the individual level, nappers with greater SWA in the post-encoding nap showed greater preference for part-words over words at testing (novelty preference), whereas those with weaker SWA tended to prefer words over part-words (familiarity preference).

Memory stabilisation: veridical memory for new word form-meaning associations.

Another line of research has investigated the effects of sleep on the stabilisation of word form–meaning associations (Axelsson et al., 2018; He et al., 2020; Horváth et al., 2015; Williams & Horst, 2014). In Horváth et al.'s (2015) study, 16-month-olds who remained awake after learning did not recognize the new associations, either immediately or at delayed testing. In contrast, infants who napped during the delay recognized the new associations after the post-learning nap (as signalled by longer looks to the target upon hearing the trained label), although they had not done so at immediate test. Similar evidence was also found around children's second birthday.

Williams and Horst (2014) exposed toddlers to new words and referents through a picture book and tested them on their ability to point at the correct referent upon hearing its label after a nap, after 24 hours, and after 7 days. Children were assigned to the wake and nap groups based on their napping habits: The nap groups consisted of children who still habitually took naps; the wake groups consisted of children who had switched to monophasic (i.e., night-only) sleep. Some toddlers heard words through the same story's being repeated several times, whereas others heard them in different stories. Toddlers who learned the new form–meaning associations through repeatedly hearing the same story remembered the words best overall, whether they napped or not. However, of the children who learned the words through different stories, those who napped after learning caught up with children who heard the same story but did not nap and reached comparable levels of memory. In contrast, children who learned the words from different stories but did not nap never caught up with the other three groups and had the weakest memory for the word form–meaning associations overall. He et al. (2020) investigated sleep effects in the acquisition of verb meanings and found that 2-year-olds' looks to a target scene upon hearing the label corresponding to that scene increased across visits if they napped after learning, while those of a wake group decreased.

Axelsson et al. (2018) examined 2.5-year-olds’ long-term memory for new word-form meaning associations learned in an active way. New words and the objects to which they corresponded were presented together with known objects; the children were asked to point to the targets without prior learning and received feedback on their performance. As in Williams and Horst’s (2014) study, the nap group was mainly composed of habitual nappers whereas most children in the wake group were nonhabitual nappers. Toddlers who did not nap after learning gradually forgot the new word form– meaning associations as their performance progressively decreased from immediate test through an intermediate delayed test and an additional test on the following day. In contrast, the nap group’s performance remained constant over the testing sessions and was significantly higher than that of the wake group after a 4-hour delay and even on the following day. Moreover, the longer the children napped, the higher their retention scores. Table 2 provides a summary of the studies of veridical memory of word–meaning pairs.

	Studies			
	Horváth 2015	**He 2020**	**Axelsson 2018**	**Williams 2014**
Participant age & groups	16 months Nap vs. wake	2.3 years Nap vs. wake	2.5 years Nap vs. Wake Nap groups: habitual nappers Wake group: nonhabitual nappers	3 years 4 groups: - same story-nap - same story-wake - different stories-nap - different stories-wake Nap groups: habitual nappers Wake groups: nonhabitual nappers

Number of tests & how long After Learning (AL)	1. immediate 2. 1.5h AL	1. 4h AL	1. Active Learning 2. Immediate 3. 4h AL 4. 24h AL	1. Immediate 2. 2.5h AL 3. 24h AL 4. 7 days AL
Significant differences between groups?	1. No 2. Yes (nap>wake)	1. Yes	1. No 2. No 3. Yes (nap>wake) 4. Yes (nap>wake)	1. Yes 2. Yes 3. Yes 4. Yes
Highlights	- Post-learning nap increased performance from immediate test. Similar time awake led to a decrease in performance. - Expressive vocabulary was positively associated with performance improvement in nappers.	- Verb representations were enhanced with sleep; without sleep, performance decayed.	- Napping shortly after learning stabilised memory performance in the nap group; - The nap group always outperformed wake group in the delayed tests; - Longer naps were associated with better retention.	- Words heard through the same story repeated were learned best overall. - Napping shortly after learning made up for the more difficult learning condition (i.e., words heard in different stories). - When story repetition was controlled for, sleep was the strongest predictor of performance on the 7 days AL test.

Table 2. Summary table: veridical memory of word-meaning pairs. *Note.* ‘Yes’ and ‘No’ indicate significant and non-significant differences between the groups’ performances respectively. ‘>’ signals better performance by the group to the left of the symbol. AL stands for ‘After Learning’.

Generalisation of form - meaning associations.

Six studies—Friedrich et al. (2015), Friedrich et al. (2020), Horváth et al. (2016), Sandoval et al. (2017), Werchan and Gómez (2014), and Werchan et al. (2021)—looked at sleep-related generalisation of word meanings. In these studies, children were familiarised with novel words and their referents and then tested on their ability to generalise the words to new but similar-looking referents. Thus, the new words were the names of new categories of referents. Friedrich et al. (2015) measured infants’ ERP responses to correctly and incorrectly matched word and referent. In previous studies, an increase in negativity had been identified between 200 ms and

500 ms in left lateral regions of the infant brain in response to correctly paired word forms and meanings; this was taken to be a sign of a child's recognition of the association between a word and its specific meaning (N200–N500 effect; Männel, 2008). In addition, increased negativity in the centro-parietal region 400 ms after stimulus presentation was interpreted as a sign of higher-level semantic processing (N400 effect).

In Friedrich et al.'s (2015) study, each child experienced all three conditions: (a) the same objects repeatedly paired with the same labels, (b) different but similar objects paired with the same category labels, and (c) objects inconsistently paired with different labels (as a control). Those who napped after exposure showed an effect similar to the N200–N500 in response to labels correctly paired with the same objects seen in the learning phase. This was taken to indicate long-term memory for the specific word–meaning associations. In addition, nappers showed an increased N400 for category labels that were incorrectly paired with a novel (i.e., previously unseen) object that did not fit the trained category, relative to correct pairs. This effect was taken to suggest that the form–meaning association was generalised and a memory representation of the category had formed. However, children who had not napped showed none of these brain responses after a delay, suggesting that they had not retained the associations or generalised the labels to novel objects of the same category. Furthermore, spindle activity was positively associated with occurrence of the N400 effect in the nap group.

Friedrich et al. (2020) adopted a similar design but exposed 14- to 17- month-olds to real word–object pairs likely to be familiar (e.g., *dog, ball, car*, etc.) and tested their ability to generalise that category to new exemplars. Infants who remained awake during the retention period showed no brain responses indicating memory for the specific word–object pairs with which they had been familiarised but showed an increased N400 effect for words paired incorrectly with both familiarised and novel objects relative to correct pairs, showing that they had lexical–semantic representations for those words. However, infants who had a post-encoding nap showed an increased N400 for words incorrectly paired with novel (but not familiarised) objects relative to correct pairs and showed an effect similar to the N200–N500 in response to the specific word-object pairs with which they had been familiarised. Furthermore, spindle activity during the post-encoding nap was positively associated with this effect (but not with the N400 effect).

Three other studies investigated generalisation of word–meaning pairs from a behavioural point of view. Horváth et al. (2016) observed that only children who napped after being familiarised with new word–object associations recognized new but similar objects as members of the same category (as evidenced by longer looks to the target objects upon hearing the trained label); they could not do so immediately after learning. Similarly, in Sandoval et al.'s (2017) study, only 3-year-olds who napped after learning managed to correctly point to the actions corresponding to the new verbs learned the day before when different actors had performed the action of the verb. This was taken as evidence of generalisation of meanings. Nonnappers, regardless of whether they were habitual nappers or not, and despite overnight sleep between learning and testing, performed significantly worse than nappers. Veridical memory (i.e., for actions performed by the same actors as in familiarisation) was tested in another pointing test where both habitual and nonhabitual nappers showed immediate veridical memory but no evidence of generalisation shortly after learning.

In Werchan and Gómez's (2014) study, children (aged 2.5 years) who remained awake in the post-learning 4-hour delay performed the most accurately when hearing the newly learned category name and being asked to point to a previously unseen item of that category. Moreover, they outperformed a third group tested immediately after learning; no statistically significant differences were found between the performances of the nap group and the immediate test group. More recently, Werchan et al. (2021) exposed 2.5-year-olds to three novel object categories and tested their ability to identify novel exemplars of those categories 24 hours after learning. One group of children napped within 4 hours of learning (nap group), while another group remained awake (no-nap group). A third group of children learned the words before a daytime nap and was tested 4 hours after awakening (nap-control). In a separate experiment, a group of children was exposed to the categories 1 hour before their usual bedtime and was tested 4 hours after waking the following morning (nighttime sleep group). The nap group showed more consistent generalisation 24 hours after learning than did either the no-nap or the nap-control groups, who did not differ statistically, and outperformed the nighttime-sleep group. Table 3 provides a summary of the studies of generalisation of word–meaning pairs.

	Studies					
	Friedrich 2015	**Horváth 2016**	**Werchan 2014**	**Sandoval 2017**	**Friedrich 2020**	**Werchan 2021**
Participant age & groups	9-16 months Nap vs. wake	16 months Nap vs. wake	2.5 years Nap vs. Wake vs. Immediate test control group (all habitual nappers)	3 years Nap vs. wake (both including habitual and nonhabitual nappers).	14-17 months Nap vs. Wake (all habitual nappers).	2.5 years Exp 1: Nap vs. No-Nap vs. Nap-control group (all habitual nappers) Exp 2: the above vs. Night-time-sleep group (napping habits not reported)
Number of tests & how long After Learning (AL)	1. 1.5h AL	1. Immediate 2. 2h AL	1. Immediate 2. 4h AL	1. 24h AL (exp1) 2. 2-3 min (exp 2)	1. 0.5-2h AL	1. 24h AL 2. 4h AL (for Nap-control only) 3. 4h after waking up in the morning (Night-time-Sleep only)
Significant differences between groups?	1. Yes (nap>wake)	1. No 2. Yes (nap>wake)	1. No 2. Yes (wake>nap)	1. Yes 2. No	2. Yes (see below)	1. Yes (Nap > Wake; Nap-control) 2. Yes (Nap > Night-time-Sleep)

Highlights	- Nappers recognised (N200-500) and generalised (N400) the word-meaning pairs, the wake group did not; - Spindle activity in the post-learning nap positively correlated with generalisation.	- A nap improved nappers' generalisation; - Wake groups' performance remained unchanged.	- Wake group showed better generalisation 4h after learning than the nap and immediate test groups. - No differences between nap and immediate test groups.	- A nap shortly after learning is associated with verb meaning generalisation 24h later, regardless of napping habits; - Nocturnal sleep alone is insufficient to generalise verb meanings, regardless of napping habits; - No generalisation observed shortly after learning.	- Nappers showed episodic memory for the familiarised word-object pairs but no semantic processing; - Spindle activity in the post-learning nap positively correlated with N200-500-like effect but not N400; - Wake group showed semantic processing of both new and familiarised pairs.	- Nappers generalised the category labels 24h after learning; - No generalisation was observed after a single nap or a single night of sleep; - Longer post-learning wake periods could decrease performance.

Table 3. Summary table: generalisation of word-meaning pairs. *Note.* 'Yes' and 'No' indicate significant and non-significant differences between the groups' performances respectively. '>' signals better performance by the group to the left of the symbol. 'AL' stands for 'After Learning'.

What evidence have researchers presented for longitudinal effects of sleep on infant vocabulary development?

Three studies—Dionne et al. (2011), Horváth and Plunkett (2016), and Knowland et al. (2022)—investigated the longitudinal relationship between current sleep patterns and later language development. Dionne et al. (2011) observed associations between sleep consolidation measured at 6, 18, and 30 months and language skills measured at 18, 30, and 60 months. A smaller ratio of daytime to nighttime sleep (i.e., a reduction in napping) at 6 months predicted larger lexicons at 18 and 30 months and at 18 months this ratio predicted vocabulary at 60 months. In Knowland et al.’s (2022) study, longer nighttime than daytime sleep between 6 and 36 months predicted larger receptive vocabularies at school entry. In addition, socioeconomic status (SES) was found to mediate the relationship between sleep consolidation and later vocabulary: Lower household SES was associated with smaller differences between nighttime and daytime sleep duration, which in turn was associated with smaller receptive vocabularies at school entry. Horváth and Plunkett (2016) found that the number of daytime naps measured at initial assessment (i.e., between 7.73 and 37.83 months of age) predicted receptive vocabulary growth positively but expressive vocabulary growth only marginally (with vocabulary measured 3 to 6 months after initial assessment in both cases). Furthermore, nighttime sleep duration was negatively correlated with expressive vocabulary development.

What evidence is there for a role for existing knowledge in sleep-related infant consolidation of newly learned words?

In two studies, Horváth et al. (2015, 2016) measured infants’ vocabulary size at the time of the study, and, in one study, Horváth et al. (2015) measured the association of that measure with sleep-related improvements in further word learning. In Horváth et al.’s (2015) study, while neither receptive nor expressive vocabulary was associated with non-nappers’ performance, expressive (but not receptive) vocabulary size was strongly and positively associated with memory improvement from immediate to post-sleep test in nappers. Friedrich et al. (2019) found a modulating effect of existing knowledge over spindle activity and post-learning memory improvement. In their study that investigated category learning, number and density of sleep spindles in post-encoding naps of 14- to 16-month-olds were significantly larger in the post-learning phase (i.e., after learning previously unknown words) than after a non-learning control condition (i.e., after exposure to words known as labels of objects of familiar categories). Moreover, not only did sleep spindle density in the post-encoding nap predict greater memory generalisation improvement on the next day, but it was stronger in those infants who did not show generalisation during encoding compared to a subgroup of infants who had already showed signs of generalisation at encoding before sleep. However, even in this latter subgroup, spindle density was a better predictor of post-learning generalisation of word–object pairings than were presleep generalisation levels.

Are there associations following word learning between electrophysiological activity in the sleeping infant brain and subsequent memory performance?

Two studies specifically investigated the associations between brain responses related to learning and brain activity during sleep. Friedrich et al. (2019) found that, during testing after sleep, an N200–N500 effect was observed after novel word learning only in 14- to 16-month-olds with higher spindle density increase in previous sleep, meaning that only these children had managed to form object categories and to appropriately associate exemplars to them. Most importantly, higher spindle density was positively correlated with stronger postsleep generalisation for unfamiliar referents as expressed in a stronger N400 effect. Friedrich et al. (2017) observed similar effects in younger infants (6- to 8-month-olds). They hypothesised that longer non-rapid eye movement sleep (when memory consolidation is believed to occur) could be positively associated with the formation of semantically-based word-meaning links (taken as evidence of a more linguistically mature infant brain) compared to perceptually-based associations (i.e., associations between sound representations and specific referents, or context-specific categories), which, according to the authors, are most typical of younger infants. Friedrich et al. (2017) found no ERP effects in the wake groups or in any of the children after immediate testing in response to any kind of category-name-to-object pairings. All the children who napped showed learning. However, the 6- to 8-month-olds in the short-nap group showed a less mature ERP effect, similar to that observed in younger infants. In contrast, the 6- to 8-month-olds in the long-nap group showed a reduced N400 effect in response to correctly paired novel objects and labels relative to incorrect pairs, indicating higher-level semantic processing of the stimuli and generalisation of word meanings at the category level.

Discussion

The studies that we reviewed investigated sleep effects on memory processes related to word learning in children under age 3 years. The variety of methods employed and age groups investigated and the small number of studies limit the extent to which we could quantitatively analyse and compare the findings. However, we could identify common themes, making it possible to compare the studies in narrative fashion. In what follows, we have addressed each review question and suggested possible directions for future research.

Methodological choices

The infant studies have mostly employed highly structured and artificial learning procedures (excluding those by Horváth & Plunkett, 2016; Horváth et al., 2015; Horváth et al., 2016); studies with older children have tended to be more diverse, including naturalistic learning conditions that used both picture books (e.g., Williams & Horst, 2014) and structured experimental designs (e.g., He et al., 2020). Testing procedures reflected the diversity of the learning procedures, with an array of behavioural memory tests (from the head-turn preference procedure to pointing) and electrophysiological measures. Furthermore, child age at first assessment varied considerably within and between studies (e.g., Friedrich et al., 2015; Horváth & Plunkett, 2016). Cross-age and cross-study comparisons were complicated by differences in the design and levels of word learning investigated at different ages. In Horváth and Plunkett’s (2016) study, age at first assessment (when sleep data were collected) varied considerably across children (from 7.73 to 37.83 months). Given the developmental variability in the relationship between daytime and nocturnal sleep, future longitudinal investigations should consider collecting sleep data from a more restricted age range.

Six of the 13 experimental studies employed multiple memory tests. These studies raised compelling questions regarding the relative importance of naps and nocturnal sleep in early word learning. First, where memory performance was measured immediately after learning and compared to that observed after a delay, whether including a nap or not (e.g., Axelsson et al., 2018; Horváth et al., 2015; Horváth et al., 2016; Williams & Horst, 2014), improvements were found in the second test only in those children who napped during the delay; in contrast, non-nappers' performance decreased or remained unchanged. Crucially, studies in which a test was included after 24 hours (e.g., Williams & Horst, 2014) found that children who had napped after learning outperformed children in the wake groups the following day, despite the wake group's having had a full night of sleep during which memory stabilisation could have occurred. Sandoval et al. (2017) and Werchan et al. (2021) found that the specific combination of a nap and nocturnal sleep was critical to learning, as neither one alone sufficiently supported generalisation of new verb and noun meanings. However, it should be noted that more time awake passed between learning and testing for the nighttime-sleep group than for the nap group in Werchan et al.'s (2021) study, and cumulative time awake prior to testing was found to be negatively correlated with generalisation performance. Multiple memory tests could be particularly instructive in within-participant designs; testing the same infants over time and taking into account the occurrence of naps and overnight sleep would provide a picture of the evolution of novel-word representations and increase understanding of the importance for word learning of, for example, morning or afternoon naps or overnight sleep (see Mason et al., 2021) as well as the impact on performance of nap length and time spent awake after learning (e.g., Hupbach et al., 2009; Werchan et al., 2021). The need for multiple tests reflects the value of longitudinal studies. Despite requiring more time and resources, only longitudinal studies can clarify the impact of the relationship between daytime and nighttime sleep on lexical development.

Another methodological point is that infants sometimes received relatively artificial, passive, and massed exposure to the stimuli (e.g., Simon et al., 2017). Only five studies employed learning methods affording an active role to the child (e.g., by allowing them to manipulate objects while the experimenter labelled them). To provide a more ecologically valid assessment of the mechanisms underlying language acquisition, future research would do well to adopt learning procedures that resemble the way in which children are naturally exposed to objects and their names.

Memory processes

This review extended to early childhood and infancy the well-established beneficial effects of sleep found in word learning in adults and school-aged children. Moreover, this review has confirmed that word learning in infancy is supported by the same domain-general mechanisms underlying the consolidation of nonlinguistic memories (e.g., Horváth et al., 2018; Seehagen et al., 2015) and is similarly supported by sleep. In terms of memory stabilisation, we found that sleep maintains (Axelsson et al., 2018; Williams & Horst, 2014) or even enhances (Horváth et al., 2015) memory for new nouns and their referents and for verbs (He et al., 2020). Similarly, sleep supports flexible use of word knowledge through such memory enhancement processes as multi-item generalisation. Sleep-associated extraction of the shared features across multiple referents (Konrad et al., 2016) also underlies the generalisation of word meanings (e.g., Horváth et al., 2016; Sandoval et al., 2017). The underlying sleep-dependent mechanisms supporting the extraction of patterns from continuous stimuli (Simon et al., 2017) are less clear (see below).

Besides generalisation of word meanings, multi-item generalisation may underlie the learning of the phonological form of a new word, as expressed in the ability to recognize the word when it is uttered by different speakers following the extraction of invariant auditory characteristics from a pool of exemplars of that word (Houston & Jusczyk, 2000, 2003). Houston and Jusczyk did not control for sleep. However, they investigated children’s recognition of newly trained word forms, either immediately or one day after familiarisation, indicating an interesting direction for future research. We are now running a study to investigate whether infant sleep supports the generalisation of word forms as it does for word meanings by employing auditory speech stimuli with no meaning attached. This will allow us to paint a more comprehensive picture of generalisation in word learning (Belia et al., 2022).

A focus on sleep effects on phonological learning may help to shed more light on another under-researched aspect of memory enhancement in word learning, namely, the sleep-associated extraction of structure from continuous speech that supports the identification of word forms and grammatical structure. Pioneering attempts to address this issue (Gómez et al., 2006; Hupbach et al., 2009) have validated the idea that sleep may improve infant sensitivity to recurrent features in running speech. Although the mechanisms underlying sleep-dependent development of this sensitivity have remained unclear, Simon et al. (2017) attempted to apply them to infant extraction of word forms from continuous speech. Simon et al. explained the preference switch found in the nap group as potentially resulting from the interference of part-words (new information) with the original words (the information to be retained), indicating weak representations for the phonological forms of the new words. A more in-depth discussion of this finding is limited by the absence of other studies investigating sleep effects on the extraction of phonological forms from running speech. However, the associations between the direction of infant preference for words versus part-words and SWA during the post-encoding nap observed in Simon et al.'s (2017) study raises intriguing issues in need of further investigation. Moreover, a focus on the differences in the consolidation of word forms learned (a) with versus without a link with meaning and (b) in isolation versus embedded in running speech could provide further insight.

A phenomenon parallel to multi-item generalisation is memory integration, that is, the assimilation of encoded representations to existing networks that is expressed in word learning as lexicalization. This review has confirmed that lexicalization in children under 3 years of age has yet to be investigated experimentally, perhaps because early vocabulary networks have generally been considered too small or sparse for lexical competition to be successfully tested. This is an important issue for future research, given the rapid growth of the lexical network as well as the unique sleeping patterns characteristic of early childhood. A first attempt to test lexicalization could be made by investigating competition while operationalizing similarity less strictly than in adult studies. Future research should consider that early word use is characterised by highly similar forms that tend to fit into fixed phonological patterns or templates (Vihman, 2019).

Longitudinal effects of sleep

Three studies examined the relationship between changes in sleep patterns and vocabulary over time. These studies confirmed the complex and still poorly understood relationship between developmental changes in sleep patterns and learning in early childhood. In Horváth and Plunkett's (2016) study, the number of daytime naps at initial assessment predicted future receptive vocabulary growth, whereas nocturnal sleep duration was negatively associated with subsequent expressive vocabulary. These findings suggested that naps are important for lexical development, perhaps providing multiple occasions to consolidate and retain new information prior to nocturnal sleep. Conversely, Dionne et al. (2011) and Knowland et al. (2022) identified the benefits of longer and less interrupted nighttime over daytime sleep to subsequent vocabulary growth, with children with longer daytime sleep also being more likely to develop language delays in later years (Dionne et al., 2011). These results supported the idea that sleep consolidation may reflect brain maturation in preschoolers (Lam et al., 2011; Riggins & Spencer, 2020).

The contradictory findings indicated that understanding the actual impact of naps and of sleep consolidation on language development is an important issue for future longitudinal investigations as well as for lab-based studies. Knowland et al. (2022) also found SES to mediate the relationship between sleep patterns and subsequent vocabulary growth, with lower SES being associated with smaller differences between daytime and nighttime sleep duration and, subsequently, with smaller receptive vocabulary at school entry. It is well established that SES predicts language outcomes in development (Schwab & Lew-Williams, 2016), and SES has been found to be associated with worse sleep overall (e.g., El-Sheikh et al., 2013). Further studies should take SES into account to gain a fuller picture of its interaction with sleeping patterns and vocabulary development and to develop better intervention practices and support plans.

Role for existing knowledge

Discrepancies between findings regarding sleep effects on child word learning are likely to be mediated by variables other than brain maturation, such as the aspect of learning being investigated and the timing and choice of sleep measures (Lukowski & Milojevitch, 2013). Another variable is the strength of the memory traces themselves (Sandoval et al., 2017). Robustly encoded memories may be less susceptible to decay over wakefulness and better maintained until nighttime; weaker memories could be more negatively affected by prolonged wakefulness and more quickly forgotten, as suggested by Axelsson et al. (2021)[1], whose study showed that ostensive naming of the to-be-learned word–object pairings at training produced strong memories at encoding that did not appear to be significantly improved after the post-encoding nap. Thus, weaker memories could show greater benefits from sleep-related memory consolidation than do stronger memories (Drosopoulos et al., 2007). Interestingly, in Williams and Horst's (2014) study, words learned through the same story versus through different stories (thus within a fixed or varying context) followed different stabilisation paths, with children hearing the words through different stories encoding the words more poorly than children who heard them through repetitions of the same story. However, after the post-learning nap, children in the different-story condition approached the memory levels of those in the same-story condition. Naps seemed to have a restorative effect, compensating for an initially more difficult learning condition. This suggested that memory strength at encoding influences the relative benefit of the sleep-dependent memory processes underlying the consolidation of new words.

The strength of memories at encoding is modulated by several variables (Stickgold & Walker, 2013); existing knowledge may be one of them. The integration of new knowledge into the neocortical system in adults is prior knowledge dependent, as new information that is more consistent with existing knowledge is likely to be consolidated more rapidly (McClelland, 2013). For example, James et al. (2019) found that both children's and adults' memory is better for novel words with more phonological neighbours but that post-sleep effects on the stabilisation of these words were larger in children who had smaller vocabularies. This may support the hypothesis that sleep-dependent memory processes can compensate for weaker encoding, as suggested in Williams and Horst's (2014) study. Interestingly, in Friedrich et al.'s (2019) study, spindle activity was found to be larger after exposure to new compared to already known information, perhaps suggesting that the strength of sleep-dependent memory processes is modulated by the individual's knowledge and related learning demands.

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[1] Although this article would meet the sample criteria outlined in the Methods section, we have not systematically reviewed it because it did not feature in the database searches when we last consulted the databases.

Existing lexical–semantic knowledge was also found to mediate post-sleep memory processing by Friedrich et al. (2020). In their study, post-nap neural correlates revealed episodic memory, but not semantic processing, for the familiarised pairings. An N400 effect was present in nappers in response to the object categories incorrectly paired with unfamiliarized referents but not with incorrectly paired familiarised referents. This indicated that the absence of an N400 effect in the latter case did not result from children's lacking lexical– semantic representations for the words at test. Instead, following the post-encoding nap recognition of the specific familiarised referents as members of known lexical categories (signalled by an effect like the N200–N500) might have been temporarily prioritised over more generalised lexical–semantic processing of the stimuli. Prioritising the stabilisation of new information consistent with existing knowledge allows recognition of similar instances in future encounters. This view seems to be consistent with the idea of selective sleep-dependent memory consolidation in adults, affecting the information consolidated and the way that it is modulated by both internal and external salience tags (e.g., degree of similarity with existing knowledge, reward, etc.; see Stickgold & Walker, 2013). This is an interesting issue that future studies could address by selecting the individual stimuli based on their degree of similarity to infants' lexical or phonological knowledge.

Beyond its local effects on learning, existing vocabulary knowledge influences the long-term acquisition of new words (Dionne et al., 2011; Horváth & Plunkett, 2016). In particular, the association between postsleep performance improvement and expressive vocabulary at the time of learning (observed in Henderson et al., 2015, and Horváth et al., 2015) suggests that the independent influences of expressive and receptive vocabulary on further word learning are worth investigating further. However, as systematic investigations of the unique role of expressive versus receptive vocabulary in new word consolidation have remained rare, it is too soon to attempt to formulate hypotheses as to the specific role of either kind of vocabulary knowledge in further word learning. Nevertheless, first word learning has been shown to involve an interplay of individual children's perceptual experience of the input and their experience in producing vocal patterns (Keren-Portnoy et al., 2010; Vihman, 2022). Future research would benefit from study of the interplay between sleep-dependent memory processes in word learning and child lexical and phonological knowledge.

Electrophysiological activity and memory performance

Direct evidence for an involvement of sleep in memory consolidation has been suggested by the positive associations between sleep spindles and generalization of a newly learned category label in a postsleep test (Friedrich et al., 2015). Evidence of sleep effects on word learning has also been seen in the direct relationship between word learning, lexical processing, and electrophysiological markers of sleep-dependent consolidation as in the studies by Friedrich and colleagues (Friedrich et al., 2015; Friedrich et al., 2017; Friedrich et al., 2019, 2020), confirming and extending findings about memory for non-language items in Kurdziel et al.'s (2013) and Kurdziel et al.'s (2018) studies.

Sleep spindles drive memory replay and are thus associated with memory consolidation. Accordingly, an association between spindle activity and word learning points towards an active role for sleep in infant word learning. However, some researchers have suggested that sleep spindles may not indicate sleep involvement in consolidation, especially considering the protracted maturation of brain areas related to memory (Gómez & Edgin, 2015, 2016). In this view memories are unlikely to be consolidated through replay before age 2 years but are instead built up through gradual and repeated exposures and are indirectly consolidated through synaptic downscaling, with sleep playing no active part. Furthermore, memories are expected to be highly specific and dependent on repeated exposures to the stimuli, with more flexible uses of memory functions observed only later in childhood (Gómez & Edgin, 2015, 2016). The behavioural and neurophysiological evidence that we reviewed has consistently shown memory benefits following sleep in infants younger than age 2 years. Thus, under some circumstances children can construct relatively stable representations and generalise them, even at young ages, especially with the support of sleep. These discrepancies suggest that further research is needed to clarify the neurological basis of sleep-dependent memory processes in infancy, perhaps with specific infant neuroimaging studies and the inclusion of multiple memory tests.

Something more: the role of naps

All the studies that we reviewed confirmed the influential role of naps in infant word learning. As we outlined above, the delayed maturation of brain areas associated with memory function may suggest that younger children need to sleep more frequently to allow their low-capacity memory system to consolidate new information. Therefore, letting go of naps would be a self-regulated behaviour emerging as the child's cognitive system becomes ready to maintain new memories over an entire day before sleeping at night (Esterline & Gómez, 2021; Knowland et al., 2022). Axelsson et al. (2018) and Williams and Horst (2014) assigned children to nap and wake groups based on their napping habits. In light of findings such as those of Esterline and Gómez (2021) and Kurdziel et al. (2013), in whose studies habitual nappers were the most negatively affected by time spent awake, we would expect wake groups (if made up mostly of non-habitual nappers) to show: (a) better performance at immediate testing compared to nappers if the initial memory traces of habitual nappers are expected to be weaker due to a less mature brain, and/or (b) maintenance or smaller decreases in memory across the wakeful delay between learning and testing on the same day. However, nap and wake group performance at immediate testing was the same in both Williams and Horst's (2014) study and Axelsson et al.'s (2018) study, and the wake group's performance decreased on the second test after an interval of time spent awake in both studies. Similar results were obtained in Sandoval et al.'s (2017) study, where non-habitual and habitual nappers benefited equally from a nap and achieved equal performance at immediate test.

In Kurdziel et al.'s (2013) study, habitual nappers benefited the most from the post-learning nap as regards memory, suggesting that they may have had more efficient nap-dependent memory consolidation than had non-habitual nappers. Thus, the source of differences in nap- and wake-group performances in William and Horst's (2014) study and Axelsson et al.'s (2018) study might not have derived from a negative effect of wakefulness but from a positive effect of naps specific to habitual nappers. However, we could draw no conclusions as to the relationship between naps, napping habits, and word learning in toddlerhood without systematic comparisons of habitual and non-habitual nappers within and between nap and wake conditions. Future studies should include an equal number of habitual and nonhabitual nappers in both nap and wake groups and systematically compare their performance with multiple memory tests (immediate, postnap, and post-nocturnal sleep). As non-habitual nappers might be more cognitively advanced, this procedure could help control for inherent cognitive differences across participants that may underlie the differences that have frequently been observed between nap and wake groups (Axelsson et al., 2021). Although it might be challenging to persuade children who no longer nap to do so, longitudinal studies could perhaps recruit children who are approaching the age range where daytime naps are usually abandoned, monitor them until they stop having a regular daytime nap (e.g., the first week or so without naps), and test them at the time that they cease to nap. As they will have just given up their naps, they could perhaps more easily be led to sleep than could be children who are more established non-habitual nappers. Including an immediate test would help exclude differences in encoding abilities across groups, potentially resulting from differences in cognitive maturation that may underlie napping habits. Although such studies would be time- and labour-intensive, they could be facilitated by remote data collection procedures that might be more child- and parent-friendly. For example, non-habitual nappers might more readily nap at home than in the lab.

Werchan and Gómez (2014) found better generalisation of new category labels in toddlers after a wake interval than following napping. Werchan and Gómez thus hypothesised that generalisation might originate in forgetting inconsistent details across referents of the same category, details which would be fortified through sleep. However, Werchan et al. (2021) advanced a plausible interpretation of their previous findings on the basis of toddlers’ generalisation as observed 24 hours instead of 4 hours after learning. In this study, the toddlers did generalise new categories 24 hours after learning, but only if they had napped shortly after being taught the new labels. Neither a single nap nor a full night’s sleep seemed to be sufficient to lead to generalisation, which was observed only after both a post-learning nap and overnight sleep. Therefore, naps may be essential for consolidating newly encoded memories for retention until nighttime sleep when longer and more complete sleep may contribute to their enhancement and thus to potential generalisation. This interpretation is consistent with studies reporting delayed effects of naps on memory performance (e.g., Hupbach et al., 2009; Sandoval et al., 2017). However, cases in which generalisation of word meanings was observed after even a single nap

(Horváth et al., 2016) or, for some children, with no sleep at all (Friedrich et al., 2019; Werchan & Gómez, 2014) suggested that research has not yet fully determined the respective roles of wakefulness, naps, and nocturnal sleep in memory generalisation across development.

Thus, findings regarding the role of naps in early memory have sometimes been contradictory. Reasons might be that, brain maturation differences aside, more robustly encoded memories could be less susceptible to decay during subsequent wakefulness and that weakly encoded memories may benefit more from sleep (Drosopoulos et al., 2007). The degree of robustness of the encoded material is highly variable across children (depending on their knowledge and experience) and across different contexts and tasks. We note, moreover, that dynamic systems theory predicts periods of stability and instability in behaviour across development, with instability often being associated with moments of marked behavioural transition (Thelen & Smith, 1994). Thus, the great variability and idiosyncrasy of sleep behaviours and their effects on memory in toddlerhood might be symptomatic of a particularly complex phase in the interplay between cognitive, physical, and neurological systems within the child.

Conclusions

The last decade has seen growing interest in understanding the effects of sleep on several aspects of lexical development, leading to a proliferation of studies in this field. Overall, this review suggests that sleep plays a positive role in word learning in early childhood, often in concert with other variables. The insights gained from the studies that we reviewed lay the groundwork for future investigations. Indeed, considerably more work is needed to understand the effects of nocturnal sleep, daytime naps, and the changing relationship between them on infant lexical development and on their interactions with other variables such as existing knowledge. Future research along these lines may have important implications given young children’s unique sleep behaviours as well as the fast rate at which they learn their language.

[i] Although this paper would meet the sample criteria outlined in the Methods section, it is not systematically reviewed as it did not feature in the database searches when they were last consulted.

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Supplementary materials

Appendix S1: The systematic review process in detail

Table S1.1 Keywords used in the searches

Main topic	**Keywords**
Sleep	Nap, sleep, sleep-dependent (-associated, -related) memory consolidation
Age	Infant, early childhood, infancy, preschool child, toddler
Memory	Cognitive development, memory consolidation, abstraction, generalisation, memory retention, memory formation, declarative memory
Language	Language development, word learning, language acquisition, vocabulary development

Table S1.2 Search strategies

Databases	**Searches**

PsycINFO	(sleep* OR nap* OR ‘daytime sleep’ OR ‘night-time sleep’) AND (child* OR infan* OR toddler* OR “early childhood” OR “preschool child*”) AND ((memory AND (“memory consolidation” OR “memory formation” OR “memory” OR “cognitive development” OR “abstraction” OR “generali?ation” OR retention OR retain OR form* OR consolidat*)) OR (language AND (learn* OR acqui* OR develop*) OR learn* OR ‘language’) OR vocabulary AND (develop* OR acqui* OR develop*) OR ‘word learning’)
Linguistics and Language Behavior Abstracts	noft(sleep* OR nap*) AND noft(child* OR infan* OR toddler*) AND noft(memory OR (consolidat* OR form* OR generali?* OR abstract*)) AND (noft(word* OR language AND (develop* OR acqui* OR learn*)) OR (vocabulary AND (develop* OR acqui* OR develop*) OR ‘word learning’)) *noft* = anywhere except full text
Web of Science	TS= (sleep* OR nap*) AND TS= ((memory AND (consolid* OR form* OR retain* OR retention OR generali?* OR strength*)) OR (language OR vocabulary OR word*)) AND TS= (child* OR toddler* OR infan*) *TS* = topic
Scopus	TITLE-ABS-KEY (sleep* OR nap*) AND (TITLE-ABS-KEY (memory AND (consolid* OR form* OR retain* OR retention OR generali?* OR strength*)) OR TITLE-ABS-KEY ((language OR vocabulary OR word*) OR learn*)) AND TITLE-ABS-KEY (child* OR toddler* OR infan*) AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (DOCTYPE,"ar") *TITLE-ABS-KEY* = Document title, abstract and keywords *Ar* = article *Re* = review

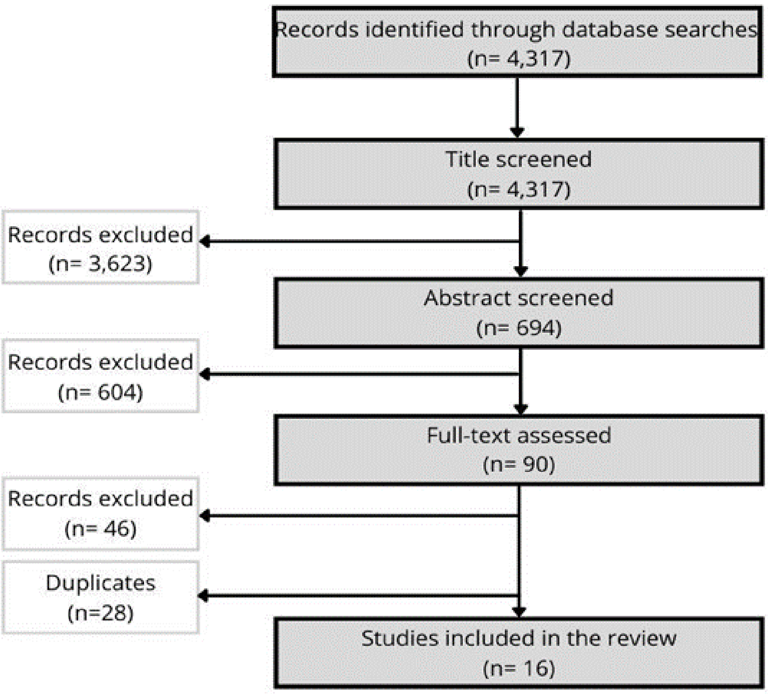

Figure S1.1 Flow chart displaying the review process.

Appendix S2: Methodological overview of the studies

								Testing		
	Sleep measures			Materials		Training		Neuro.		Behav.
	x				x		x			x
			x							
		x		x		x			x	
		x		x		x		x	x	

		x				x				x		x	x			
		x				x	x			x		x	x			
			x					x		x					x	
	x			x			x				x				x	
	x			x		x					x				x	
			x													
				x												
	x		x					x		x						x
		x		x	x				x					x		
			x			x				x						x
	x					x				x					x	x
							x				x					x

Appendix S3: Details about the design, procedures, and results of the studies reviewed

Study	Participant number and age; Design	Delay	Type of sleep	Stimuli	Procedure	Main findings

Simon et al. (2017)	37; 6.4 – 7.2 months; Cross-sectional (nap group vs. wake group)	Depending on nap length of infants in nap group	One nap	Artificial language made from monotone syllables, no cue suggesting word boundaries.	Children were exposed to the strings while engaged quietly in other activities. Then, children either napped or remained awake. Then, their recognition was tested via HTPP, where they were presented with words vs. part-words (i.e. formed by two adjacent halves of two contiguous words).	No significant difference between the two groups. Nap group's preference (non-significant) was found for part-words over words in Block 1 and vice-versa in Block 2; interaction of Block by Trial type found in nappers. SWA magnitude was associated with preference direction.
Friedrich et al. (2015)	90; 9-16 months (mean: 12.65); Cross-sectional (nap group vs. wake group)	Approx. 1.5h	One nap	Auditory: disyllabic pseudowords as labels of new object category. Visual: pictures of pseudo-objects belonging to the categories.	Children had on-screen exposure to the stimuli. Then, after a delay where only half of the children had a nap, their ERPs at test were recorded, in two conditions: incorrect vs. correct category pairing conditions. In addition, their sleep spindles activity was recorded.	No N200-500 nor N400 effect in wake group. In nap group, both increased N200-500 to correct pairings and decreased N400 to correct pairings were found. N400 effect was positively associated with sleep spindles activity during post-learning nap.

Horváth et al. (2016)	28; 16 months; Cross-sectional (nap vs. wake group)	Approx. 1h	One nap	Two new category labels (pseudowords), four new objects belonging to each category (two original objects and two generalisation objects).	Presentation of two new toys and their names (original objects) and two similar objects, only labelled with “it” or “this” (generalisation objects). Then, on-screen training and immediate test, followed by delay (where half of the children napped, and the other half did not). Looking to correct vs. incorrect assignment of the generalisation objects to their category labels was measured after the delay.	Only nappers consistently preferred looking at the correct object-category assignments; non-nappers showed no preference. Generalisation effect detected only after the retention interval inclusive of sleep, not at immediate test. The two groups’ performance was the same at immediate test.
Sandoval et al., (2017)	39; 3;0; Cross-sectional (non/habitual nappers – nap group; non/habitual nappers- wake group).	24 hours	One nap, one night of sleep	Two novel pseudowords meaning two distinct whole-body actions (video recorded).	On-screen exposure to the new actions and their labels. Children were asked to do their best to learn the new actions. The nap groups napped after exposure. All four groups were tested on the following day on the recognition of the same actions performed by different actors.	Only the nap groups recognised the actions corresponding to the newly learned verbs, even when performed by different actors, thus showing evidence of generalisation. Non-nappers, regardless of their napping habits and despite the full night of sleep between learning and testing, performed significantly worse than nappers.

Werchan & Gómez (2014)	30; 2;5; Cross-sectional (nap group; wake group, immediate test group)	0 (immediate test group) 4 hours (nap and wake groups)	One nap	Pictures of three different but similar object exemplars belonging to each category (each labelled with a different pseudoword).	Presentation of three objects in each category within carrier phrases (e.g. Look at the *dax!*) and of a distractor object. The test was a forced four-choice alternative recognition test, between a new instance of the object category, a novel object, the distractor and a familiar toy.	Better recognition found in the no-nap than the nap group and the immediate-test group. No differences were found between the nap and immediate-test group's performance.
Horváth et al. (2015)	38; 16 months; Cross-sectional (nap group vs. wake group)	0 (immediate test) 1.5 hours (delayed test)	One nap	Two new pseudoword-object pairings	Two new objects introduced one at a time, each labelled nine times with carrier sentences. Then, on-screen training (one block of two familiar words (presented individually either L or R) and one block of two new words (presented individually either L or R)). Infants had an immediate test, where a block of two familiar words and a block of two new words were presented. After a delay where half of the children had a nap and half remained awake, testing was repeated.	No between-group differences at immediate test. At delayed test, nappers' performance had increased whereas that of non-nappers decreased compared to immediate test, and the former significantly outperformed the latter. Neither receptive nor expressive vocabulary was associated with performance in the no-nap group. Expressive vocabulary (but not receptive) was strongly and positively associated with the shift in performance from immediate to post-sleep test in the nap group.

Williams & Horst (2014)	48; 3;0; Cross-sectional (four groups: same story-nap group (1); different stories-nap group (2); same story-wake group (3); different stories-wake group(4))	0 (immediate test) 2.5 hours (second test) 24 hours (third test) 7 days (fourth test)	One nap, one night of sleep, multiple nights of sleep (and presumably multiple naps for habitual nappers).	Two new pseudoword-object pairs.	The new words were embedded in story books. Half of the children were read the same story three times; the other half were read three different books. After being read the book(s), children's initial recognition of the new words was tested via a pointing game. Then, the nap groups took their nap while the no-nap groups played. Recognition was tested again after 2.5h, 24h and 7 days from initial exposure.	Group 1 performed the best, followed by Group 3. Group 2 performed just as well as Group 3 after a night's sleep and in subsequent tests. Group 4 performed the worst. Better memory found after 24h than after 2.5h or at immediate test, and after 7 days than at immediate test. After 2.5h, story repetition predicted 23% of the variance; sleep and story repetition together predicted 50%. After 24h, sleep and story repetition together predicted 39%. After 7 days, nap became the strongest predictor when story repetition was controlled for.
Xiaoxue He et al. (2020)	42; 2;3 years; Cross-sectional (nap vs. wake group).	4 hours	One nap	Videos of actions performed by actors (targets were always causative actions)	Training: videos of one speaker talking about the target action, e.g. "the man is going to *moop* the lady"). Four hours later, target and distractor actions presented + prompt to look at the target action ("do you see mooping? Find mooping!").	In the nap group, proportion of look towards the target scene increased from visit 1 to 2. In the wake group, it decreased.

Friedrich et al. (2019)	30; 14 to 16 months; Within-subject design (three lab sessions, each on a different day).	24 hours	One nap, one night of sleep	Eight exemplars of eight different similarity-based categories (nonwords). Four more exemplars for each category at test. Control session: eight exemplars of eight known categories.	Day 1: exposure to new similarity-based categories, consistently and inconsistently paired with referents. Day 2: recording of ERP responses to new exemplars which were either correctly or incorrectly paired to their category. Day 3 (one week later): control session with same test procedure but exemplars of known categories (dog, ball, etc.). After learning and control sessions, all infants napped.	Post-learning nap (day 1): longer NREM and more frequent and intense spindles compared to post-control session nap. After the learning session, only the group with bigger spindle density growth showed the word form priming effect. Only the group with high density showed parietal memory effects, whose polarity and distribution resemble to N400. Neither N200-500 nor N400 effects were present in training session. Children with weak spindle activity did show N400 in 2nd half of training, while children with strong spindles did not. However, immediate generalisation did not predict post sleep generalisation as strongly as spindle activity.

Friedrich et al. (2017)	107; 6 to 8 months; Cross-sectional (short-nap, long-nap, wake group, based on spontaneous nap duration.	1 hour (as the wake group had a shorter delay, because not able to say awake for that long, delay length was a covariate).	One nap	As in Friedrich et al., 2019	Learning: stimuli were presented in inconsistent pairing condition (i.e., every word paired to every object once, to teach word form but to avoid form-meaning pairing) and in consistent pairing condition (i.e. category words were paired with eight exemplars each). At test, ERP responses to correct- and incorrect category-exemplar pairings (with four new exemplars) were recorded.	Wake group showed no effect. Short-nap infants showed brain responses of 3-month-olds (perceptual-associative memory). Long-nap infants showed semantic priming effect (N400). This shift was positively associated with NREM stage 2 length and spindle activity. The N400 effect was correlated with number of spindles in the long-N2 group, but not in the short-N2.
Axelsson et al. (2018)	40; 2;5; Group assignment was done based on whether children spontaneously napped during the 4h interval between training and test.	0 (immediate test) 4 hours (second test) 24 hours (third test)	One nap, one night of sleep	Four novel word-object associations (nouns) in competition with 58 familiar words, selected from OZI (Australian adaptation of the CDI).	Learning via referent selection, where eight trials had one novel and two familiar objects, and other eight trials were with familiar words only. Feedback was provided during this phase. Then, three testing sessions: immediate, post-nap (after 4h), post-nocturnal sleep (following morning). At test, the four novel objects were displayed on the screen and children were asked to point to the one they heard.	Both groups performed above chance during learning, with similar accuracy. Same at immediate test. After a delay, nappers performed above chance and better than non-nappers. Same after nocturnal sleep. No-nap group had steady decline in retention scores. Nap duration positively correlated with retention post-nap.

Dionne et al. (2011)	1029; 6, 18, 30 months (initial measures); 18, 30, 60 months (final measures); longitudinal.	n/a	n/a	n/a	Language skills measured via CDI & Peabody; Sleep consolidation measured via by the Quebec Newborn Twin Study	Children gradually slept longer and more consecutively at night than during the day (i.e. gradually smaller day/night sleep ratio). Children with language delays at 60 months had had more immature sleep consolidation at 6 and 18 months.
Horváth & Plunkett (2016)	246; Initial assessment: between 7.73 and 37.83 months; longitudinal.	n/a	n/a	Sleep and Naps Oxford Research Inventory (SNORI); Oxford Communicative Development Inventory (OCDI)	After an initial assessment of both sleep behaviour and vocabulary, OCDI data were collected again between 2 and 8 times more.	At initial assessment, sleep efficiency (i.e. total time spent asleep/sleep duration) was positively correlated with both receptive and expressive vocabulary, which also correlated with number of naps. The number of daytime naps and sleep efficiency predicted receptive vocabulary and only marginally expressive vocabulary. The length of nocturnal sleep was negatively correlated with expressive vocabulary development.

Knowland et al. (2022)	1,538 in total (354 with vocabulary data). Sleep assessed at 6, 12, 18, 24 months) and 36 months. From *Born in Bradford 1,000* database.	n/a	n/a	British Picture Vocabulary Scale-2nd Edition; parents' estimation of infants' day- and nighttime sleep times.	British Picture Vocabulary Scale-2nd Edition was administered to children at school entry; parents' estimation of duration of day- and nighttime sleep was collected once at each data collection point and was taken to represent infants' sleeping habits over previous days. SES information was available in the dataset.	Day-time sleep decreased over the 30 months. More nighttime compared to daytime sleep over the 30 months predicted better vocabulary at school entry. When controlling for the nighttime vs. daytime sleep ratio, SES emerged as an additional predictor of later receptive vocabulary.
Werchan et al. (2021)	54; 29-36 months; cross-sectional: Wake (post-learning wakefulness), Nap, Nap-Control (nap approx. 1h after learning), Night-Control.	24h for Nap and Wake groups. For Nap-control group, 4h from waking up from nap. For the Night-control group, learning occurred within 2h before bedtime and testing within 4h from waking up in the morning.	Nap + Night of sleep (Nap); Night of sleep (Night-control); Nap (Nap-control)	Pictures of three different but similar object exemplars belonging to each category (each labelled with a different pseudoword).	Presentation of three objects in each category within carrier phrases (e.g. Look at the *dax!*) and of a distractor object (unlabelled). The test was a forced four-choice alternative recognition test, between a new instance of the object category, a novel object, the distractor and a familiar toy.	The Nap group generalised better than the Wake and Nap-Control groups (whose performances did not differ). Therefore, nighttime sleep was essential for generalisation to be observed. Night-control group 's performance was not different from Wake's and Nap-control's, but it was worse than Nap's. However, longer wake time prior to testing negatively correlated with subsequent generalisation.

Friedrich et al. (2020)	60; 14 to 17 months (mean: 15.11); cross-sectional: wake (unlikely to nap in the 2h prior to testing), nap group (likely to nap within 1h prior to testing).	0.5-2h.	One nap	8 pictures of objects belonging to each of 8 categories (tot: 64).	Encoding: exposure to familiar objects paired with their category label. Test: infants' ERPs were measured in response to the same pairings and: a) incorrect pairings; b) incorrect pairings with new objects of the same categories; c) correct pairings with new objects of the same categories. New objects belonged to the familiarised categories but were not in the encoding session.	N400 effect was visible in both groups in response to new objects correctly paired with their category, but only in the wake group in response to the pairings presented at encoding. Nappers showed N200-500 effect for pairings presented at encoding and it correlated positively with sleep spindles in the post-encoding nap.

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Paper 2. Word form generalisation across voices: the role of infant sleep.

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Abstract

Sleep is fundamental to memory and learning. A growing body of research shows that infant sleep supports multiple aspects of infant language development, such as the generalisation of common visual features across different but similar referents (i.e., category learning) and the extraction of the underlying structure of continuous auditory stimuli. The relative role of daytime naps and nocturnal sleep in these memory generalisation processes is debated, with some studies observing significant generalisation following a post-encoding nap and others following nocturnal sleep, but only in cases where a post-encoding nap had occurred on the previous day. This study investigates the relative role of daytime naps and nocturnal sleep in infant generalisation of newly encoded phonological forms, as observed in the infants' ability to recognise the same word forms across different voices. This ability involves the extraction of constant auditory features from a pool of variable auditory instances and is thus an example of memory generalisation. We found a significant increase in word form generalisation after a night's sleep only in infants who napped shortly after first exposure to the words, thus providing the first evidence that the combination of a post-encoding nap and nocturnal sleep is critical for long-term generalisation of novel word forms. This study is the first systematic investigation of the role of sleep in the memory processes involved in infant word form generalisation. This ability entails recognising words across different voices and is thus crucial to understand language. Our findings contribute to the current understanding of the mechanisms involved in early phonological development and of the relative importance of daytime naps and nocturnal sleep in memory generalisation in infancy.

Introduction

To acquire language, infants must form long-term memory representations of the sound patterns of words and recognise those patterns across different instances of the words. At the same time, people retain highly detailed linguistic, auditory and indexical properties of speech (e.g., Goldinger, 1996, 1998; Pufahl & Samuel, 2014). Thus, recognising different heard tokens of the same word as such entails extracting constant auditory features from a pool of variable instances. Several studies suggest that sleep supports similar processes of knowledge abstraction in other domains in children, e.g., the extraction of invariant visual features across similar-looking objects and the ability to recognise them under the label of the same object category (e.g., Konrad, Seehagen, et al., 2016), or the extraction of the underlying structure of continuous stimuli (e.g., Gómez et al., 2006, Hupbach et al., 2009).

Different theories provide different explanations of the mechanism whereby sleep supports knowledge consolidation and abstraction, in both adults and children (e.g., Gais & Born, 2004; Lewis & Durrant, 2011; Tononi & Cirelli, 2003). The underlying evidence across the existing theories suggests that the synapses activated during wakefulness are stronger after a period of time spent asleep compared to a similar amount of time spent awake (Tononi & Cirelli, 2003; Lewis & Durrant, 2011). This, together with the enhanced memory performance often observed after a period of sleep, suggests that the reinforcement of synaptic connections during sleep leads to stronger and better connected memory traces. As these connections link memory traces sharing common features, they are the basis for the formation of categories and generalised memories more broadly (Lewis & Durrant, 2011). So, the strengthening of the connections between memories during sleep leads to better remembered and generalised memories, after sleep.

Specifically, slow-wave sleep actively promotes memory consolidation and generalisation during sleep (see Rasch & Born 2013). And indeed, greater slow wave sleep activity (SWA) during a post-encoding nap sleep is associated with greater post-sleep recall of emotional memories after subsequent overnight sleep (Kurdziel et al., 2018). In some instances, generalisation of meanings has been observed only when both a nap and nocturnal sleep followed children’s first exposure to the new objects and their labels; in these studies, memory generalisation was not observed after a single nap or a single night’s sleep, but only when both of those had occurred (Werchan et al., 2021). Furthermore, a nap occurring closer to the time of encoding sometimes predicted better generalisation performance (Hupbach et al., 2009; Sandoval et al., 2017). Furthermore, longer naps sometimes predicted better generalisation of the meanings of newly learned words (e.g., Friedrich et al., 2017). Evidence for a direct involvement of sleep in memory generalisation processes comes from studies where the electrophysiological activity in the sleeping brain predicted generalisation of a newly learned category label in a post-sleep test (e.g., Friedrich et al., 2015). However, the effect of sleep on the extraction of constant auditory features of word forms as described above has not yet been studied.

Research suggests that infants retain detailed information about the auditory properties of words and that their ability to extract and generalise invariant patterns across different auditory instances of the same word may evolve with age (Houston & Juszcyk, 2000, 2003; Singh et al., 2004). Infants aged 7.5 months were able to recognise the same words only across voices of the same sex, whereas 10- month-olds could do so across speakers of different sexes, but only immediately after familiarisation with passages containing the words (Houston & Jusczyk, 2000). This ability was not retained across a 24-hour delay; neither 7.5- nor 10-month-olds recognised words uttered by a novel same-sex speaker after having heard another speaker produce different instances of the same words the day before (Houston & Juszcyk, 2003). Nevertheless, 7.5-month-olds recognised these words embedded in passages uttered by a novel speaker even 24 hours after hearing them in the original voice, if they were presented together with passages spoken in the original voice (Houston & Juszcyk, 2003). These studies tested infants on their ability not only to recognise familiarised words heard in an unfamiliar voice but also to identify those words in running speech after having heard them as individual tokens. Thus, the extraction of auditory properties across different word tokens could potentially have been more challenging because of the additional segmentation task that infants underwent at test (see Floccia et al., 2016).

Given the research briefly summarised above, our study is designed to shed more light on the potential role of sleep in the generalisation of newly learned word forms in infancy. Houston and Juszcyk (2003) tested infants' ability to recognise words across different voices after 24h from exposure to the words, they did not examine whether and how sleeping during this delay could have influenced infants' recognition abilities. We build on the design employed in Houston and Juszcyk (2003), but in addition to the original design, we specifically investigate the effects of sleep on infants' word form recognition across voices. Based on evidence suggesting that British English-learning infants rarely succeed in word segmentation paradigms (Floccia et al., 2016), we use as stimuli lists of nonwords instead of passages, in both the familiarisation and testing phases. In our study, after familiarising infants to six nonwords (see below), we test infants' recognition of those nonwords across different voices, both after a nap or a similarly long wake interval and on the following day. We test infants aged around 8 months, as this is the age at which word form generalisation is still developing (see Houston & Jusczyk, 2003) and, as such, potentially more likely to benefit from post-encoding sleep. Note that as a group, Houston and Jusczyk (2003) found that 7.5-month olds did not recognise the familiarised words a day after familiarisation (they did not test for recognition after a 1-2 hour delay). Accordingly, we do not expect the infants as a group (if we disregard whether they have napped or not after familiarisation) to recognise the words after a 24-hour delay. We have three main hypotheses:

1. If naps individually support the extraction of invariant auditory features and underlie word form generalisation, we expect that having a nap after exposure to several tokens of nonwords uttered by a single speaker will increase infants' chances of recognising those nonwords when they are produced by a novel speaker. That is, we expect to observe significantly better recognition of the word tokens when produced in a new voice after a single daytime nap.

2. If naps combined with overnight sleep are critical for long-term consolidation of invariant auditory properties of word tokens, we expect to observe recognition of the word tokens when they are presented in a novel voice 24 hours after first exposure, but only in infants who had a nap after first exposure to the words.

3. If a night's sleep alone is sufficient for generalisation, we expect significantly better recognition of the word tokens in a new voice after a night's sleep, regardless of whether an infant napped following first exposure to the words or not.

This study was run during the COVID-19 pandemic. Therefore, we developed an online design to collect data remotely. This study was pre-registered (https://osf.io/ucqa8/?view_only=2075f43a0b554ce6817544d64ca9116b).

Materials and Methods

Participants

The final sample included 45 participants, aged between 7.5 and 8.5 months (+/- one week) (M = 8 months, range = 7;15 - 8;24). Families could take part from anywhere in the UK. They were recruited through online advertisement in UK parenting communities and websites and parent groups on social media. To participate, families needed a working computer and a webcam, or a laptop or tablet with a built-in camera, as well as internet access. We initially allowed participants to use smartphones to participate, given the relative accessibility of this kind of device. However, we then realised that the screen on these devices was probably too small to direct the infant's attention to the stimuli, so we did not include these participants in the final analysis. To ensure comparability across participants, all infants came from monolingual English households and had no known speech or hearing problems or developmental disorders.

Participants were randomly assigned to a Nap (*n* = 23; M = 8;0; range = 7;15 - 8;24) or a Wake group (*n* = 22; M = 8;3; range = 7;15 - 8;20). Participants in the Nap group were expected to nap during the period between the familiarisation and the first recognition test (henceforth, the retention period), whereas those in the Wake group were expected to remain awake. We considered a nap to be any parent-reported bout of sleep occurring during the retention period. Before the post-delay test (see below), every parent was asked whether their child fell asleep in the retention period and for how long, as well as the time their child woke up. Every child in the Nap group had one nap during the retention period. If a child was not reported to have napped during this time, it was excluded from the analysis. Likewise, we excluded from the analysis infants in the Wake group who napped during the retention period. The duration of the delay between familiarisation and nap onset was computed based on the nap duration and nap onset time information provided by the parents. The minimum nap length reported by the parents was 10 minutes, which aligns with other studies in the field (e.g., Friedrich et al., 2017).

Data from an additional 27 infants were discarded because their behaviour during the retention period (i.e., whether they were asleep or awake) did not correspond to the group they had been assigned to (*n* = 5) or due to: inattentiveness during the training or testing sessions (*n* = 5), issues with internet connection (*n* = 4), poor video quality that compromised accurate coding of the child's looking behaviour (*n* = 1), child moving out of frame (*n* = 2), child fussiness (*n* = 6), problems associated with the kind of device used to connect to the call with the experimenter (*n* = 1), the retention period lasting more than 3 hours (*n* = 1), experimenter error (*n* = 1), the child's age exceeding the age range for participation in the study (*n* = 1).

A sample size of 90 participants (45 per group) was estimated via an a priori power analysis. Based on the findings of a previous study adopting a similar procedure to ours (Houston & Jusczyk, 2003, Experiment 1), a power analysis for a one-sample t-test (80% power, .05 alpha) suggested a sample size of 43 to detect a medium effect size of .44. As Houston and Jusczyk's (2003) analysis was based on a same-subject design and there are currently no studies adopting a similar procedure in a between-subject design with sleep as a variable, we adopted a conservative approach and considered the suggested sample size as a minimum for each group, in order to detect an effect (if any) in either group. In addition, as there were 9 counterbalancing orders (see Design section), the sample size for each group was adjusted to 45. We used the Sample size calculator tool provided by AI-Therapy Statistics (https://www.ai-therapy.com/psychology-statistics/sample-size-calculator). However, due to time constraints, we realised part way through the data collection that we would have not attained the planned sample. We therefore set a final date for recruitment as our stopping rule. As a result, only 50% of the target sample size was attained. Given that power analyses can be potentially misleading when dealing with small, highly variable samples (Pek et al., 2022), we cautiously interpreted the results of the power analysis as a rough guide and determined that our final sample size was justifiable.

Because group assignment was based on children's napping behaviour, double blinding was not possible. However, participants' parents were unaware of the existence of two experimental groups within the study until the end of the experiment, when they were debriefed. Although the experimenter (i.e., the first author) who interacted directly with the children and analysed their data was aware of the assigned groups, she was kept unaware of which stimuli were being presented to each child in any given trial in the following way. To counterbalance which nonwords were presented in which voice, and whether as familiarised or novel stimuli, nine experimental orders were created (see Table 1). Habit (Oakes et al., 2019) was used to build the experiment and its nine counterbalancing orders.

An independent researcher assigned a random number to each of the nine counterbalancing orders. The experimenter was blind to the mapping between numbers and orders. When playing the stimuli to the participants, the experimenter used these numbers, not knowing which files they would call up. In addition, before running each experimental session, the experimenter turned off their own speakers to avoid hearing the stimuli being played to the participant.

Design

The study followed a two-way mixed-design. Participants in the two groups underwent the same three experimental sessions (i.e., familiarisation, post-delay test and post-24h test) and participants' performance was compared both between- and within-subject, to assess the impact on word form recognition of the occurrence of post-encoding nap vs. wakefulness as well as of nap and overnight sleep. The familiarisation and the post-delay test were scheduled around each infant's usual napping/waking times (see Participants section). Thus, infants in the Wake group were not deprived of naps but their sessions were scheduled so that they were unlikely to nap during the retention period. The post-delay test was scheduled between 1 and 2 hours after familiarisation, and the post-24h test was scheduled 24 hours after familiarisation.

Materials

Three different female speakers of various ages recorded each of six nonwords. All three are native or native-like speakers of British English, with a Northern English accent. Each nonword was produced seven times in succession, with the resultant utterance produced with the intonation of a sentence (with focal stress on the 5th repetition), even though it is composed of seven repetitions of a single nonword (see Werker et al., 1998). The speakers were asked to imagine they were speaking a language with only one word in its vocabulary but with the prosodic contours that are typical of British English. They were instructed to read the nonwords as if they were talking to a young child, with a clear and lively intonation. The voice in which the children heard the words was different for each session. Therefore, both speaker identity and familiarised words were counterbalanced across participants, producing a total of nine different counterbalancing orders (3 speakers * 3 pairs of words), as shown in Table 1.

The nonwords used as stimuli in this study were:

Poblet [ˈpɒblət], *Gosset* [ˈgɒsɪt]

Taplin [ˈtæplɪn], *Duffin* [ˈdʌfɪn]

Kangle [kæŋgəɫ], *Bizzle* [ˈbɪzəɫ]

Order	**Day 1 - familiarisation**	**Day 1 - test**	**Day 2 - test**
A	*Poblet, Gosset* (speaker 1)	*Poblet, Gosset vs. Taplin, Duffin (*speaker 2)	*Poblet, Gosset vs. Kangle, Bizzle (*speaker 3)
B	*Poblet, Gosset* (speaker 2)	*Poblet, Gosset vs. Taplin, Duffin (*speaker 3)	*Poblet, Gosset vs. Kangle, Bizzle (*speaker 1)
C	*Poblet, Gosset* (speaker 3)	*Poblet, Gosset vs. Taplin, Duffin (*speaker 1)	*Poblet, Gosset vs. Kangle, Bizzle (*speaker 2)
D	*Taplin, Duffin* (speaker 1)	*Taplin, Duffin vs. Kangle, Bizzle* (speaker 2)	*Taplin, Duffin vs. Poblet, Gosset* (speaker 3)
E	*Taplin, Duffin* (speaker 2)	*Taplin, Duffin vs. Kangle, Bizzle* (speaker 3)	*Taplin, Duffin vs. Poblet, Gosset* (speaker 1)
F	*Taplin, Duffin* (speaker 3)	*Taplin, Duffin vs. Kangle, Bizzle* (speaker 1)	*Taplin, Duffin vs. Poblet, Gosset* (speaker 2)
G	*Kangle, Bizzle* (speaker 1)	*Kangle, Bizzle vs. Poblet, Gosset* (speaker 2)	*Kangle, Bizzle vs. Taplin, Duffin* (speaker 3)
H	*Kangle, Bizzle* (speaker 2)	*Kangle, Bizzle vs. Poblet, Gosset* (speaker 3)	*Kangle, Bizzle vs. Taplin, Duffin* (speaker 1)

I	*Kangle, Bizzle* (speaker 3)	*Kangle, Bizzle vs. Poblet, Gosset* (speaker 1)	*Kangle, Bizzle vs. Taplin, Duffin* (speaker 2)

Table 1. The nine experimental orders.

Procedure

The structure of our paradigm was identical to that employed in Houston and Jusczyk (2003), but modified for familiarisation duration (increased from 30 seconds to 45 seconds for each familiarised word, see below). This change was deemed necessary due to the employment of nonwords in our paradigm, as opposed to familiar words in Houston and Jusczyk's study.

During the familiarisation phase on Day 1, infants heard several repetitions of two lists made up of multiple repetitions of one nonword each, uttered by the same talker. Each nonword list was played for 45 seconds. After the retention period, during which some of them napped and others stayed awake, infants underwent a central fixation task (Cooper & Aslin, 1990), in which they heard two lists containing the same two nonwords and two other lists with one new nonword each. All four lists were produced by a novel talker. On the following day (Day 2), infants again underwent a central fixation task, in which they were exposed to the two familiarised nonword lists and to two other lists containing one new nonword each, all four produced by a third novel talker (see Figure 1).

The familiarisation and test phases were run on Habit, via screen sharing over a videocall on Zoom. Before each session, parents were asked to connect to the videocall from as quiet a room as possible and to move all toys and potentially attractive objects out of the child's view and reach. They were instructed to seat the child in a highchair or on their lap, facing their device, which they would have previously positioned on a flat, stable surface. Each call lasted approximately 15 minutes.

To familiarise the infants with the task, a pre-familiarisation stimulus was presented before familiarisation. The pre-familiarisation stimulus consisted of a colourful abstract moving shape, not paired with sound. In all three sessions of the experiment, the nonword stimuli were presented paired with this same colourful abstract moving shape. Although a static visual stimulus is usually paired with the auditory stimuli in in-lab central fixation procedures, this failed to direct the infants' gaze to the screen in our online design and thus had to be replaced with the more engaging moving stimulus. In the familiarisation phase on Day 1 the two lists were presented one after the other and infants' looking time to the screen (i.e., the sound source) was recorded online. The familiarised words were presented in an alternating fashion until the infants accumulated a total looking time of 45 seconds for each word. If infants accumulated 45 seconds of listening to one nonword and not the other, the nonwords continued to be played in an alternating fashion until the looking time threshold was reached for both. In both tests, the familiar-nonword and the novel-nonword lists were presented once each in each of four blocks, in a random order within each block, totalling four repetitions per nonword-list at each testing session (see Houston & Jusczyk, 2003).

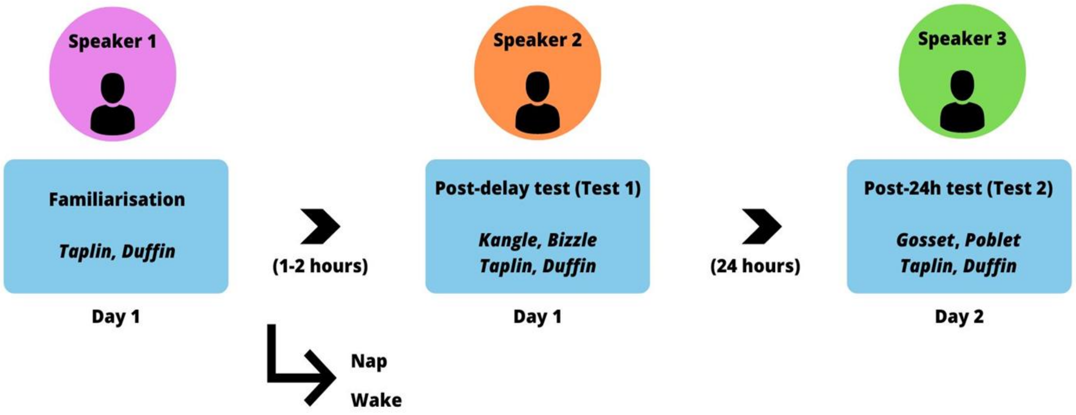

Figure 1. Experimental design. All children participated in three experimental sessions, over two days. On Day 1, they first took part in a familiarisation phase where they heard multiple repetitions of two nonwords (e.g., *taplin* and *duffin*), uttered by the same speaker (e.g., Speaker 1). Then, between 1 and 2 hours later, the post-delay test occurred (Test 1). During the 1-2 hour delay, some infants naturally stayed awake (Wake group) whereas others naturally napped (Nap group). At the post-delay test (Test 1), infants heard multiple repetitions of the familiarised nonwords (e.g., *taplin* and *duffin*) and two novel nonwords (e.g., *kangle* and *bizzle*), all uttered by a novel speaker (e.g., Speaker 2). On the next day (Day 2), 24h after familiarisation, all children underwent a second test (Post-24h test, or Test 2) identical to the post-delay test, where they heard the familiarised words again (e.g., *taplin* and *duffin*) and two novel nonwords (e.g., *gosset* and *poblet*), all uttered by a third speaker (e.g., Speaker 3).

The dependent variable was each infant's looking time to the screen (i.e., the sound source) in any given trial of the test phases. Looking time was coded online by the experimenter via Habit[2]. A significant difference in average looking time between the familiarised and the novel nonword lists was interpreted as evidence for the infants being able to tell the two stimuli apart, and thus of their recognising the familiarised words in a new voice. On the other hand, no difference in attention to the familiar- vs. novel-nonword lists was interpreted as the infants treating the two lists as equally novel, suggesting that they were not able to generalise the familiarised words to novel voices.

Results

Coding

We first transformed each infant's raw looking times into z-scores and then calculated the absolute value of the difference between the mean z-scores of the looks to the familiar words and that of the looks to the novel words for each child (*fam-nov*). The reason for this was twofold. First, z-scores were chosen over raw looking time scores because infants may naturally differ in the overall time they spend looking at screens. So, for example, a 100ms difference between looks to familiar and novel words may represent a more significant difference for an infant with shorter looks than for an infant with longer looks on average. As z-scores provide a measure of the distance between each value to the sample mean in units of standard deviation rather than in ms, they represent a more standardised measure of the difference of looking times to the familiar and novel words and allow more equitable comparisons across participants. Second, we employed absolute values of the difference of looks to familiar and novel words in z-scores to ensure that the analysis focused on the magnitude, rather than the direction, of the difference between looking time to familiar and novel words. We reasoned that such a difference could take the form of a novelty or familiarity effect (which would be represented by negative and positive values, respectively), but we had no strong a priori reason to predict the direction of the effect (novelty vs. familiarity). So, we believe that employing absolute values helped us avoid introducing a directional bias into the analysis. Ultimately, using absolute values simplifies the interpretation of results. In principle, different children within the sample could show novelty and familiarity effects, which would make the interpretation of the results potentially more

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[2] The looking times are based on the experimenter's measurements done in real time. No reliability of the looking times has been carried out.

confusing. In our coding scheme, a value of 0 in the dependent variable indicates no difference between looking duration to the familiar and the novel stimuli and, therefore, no recognition. The larger the value, the larger the difference between looks to the familiar and novel stimuli, the stronger the evidence for that child recognising the familiarised words, irrespective of whether the difference leans toward novelty or familiarity.

Analysis

Main analysis

Table 2 represents the average age, the length of the delay between the first exposure to the words and the first recognition test and time of day for each of the three sessions across groups, as well as the length of the nap and that of the delay between familiarisation and nap onset for the Nap group.

Group	Average age in days (sd)	Average delay between familiarisation and test 1 in minutes (sd)	Average time of the day of familiarisation (sd in hours)	Average time of the day of post-delay test (sd in hours)	Average time of the day of post-24h test (sd in hours)	Average nap duration in minutes (sd)	Average familiarisation-nap delay length in minutes (sd)
Nap group	242 (13.26)	113 (33.89)	10:59 (0.078)	12:52 (0.078)	11:15 (0.078)	50 (26)	36 (30)
Wake group	245 (10.02)	94 (23.92)	11:25 (0.095)	12:59 (0.096)	11:49 (0.086)	n/a	n/a

Table 2. Average age, delay length and time of day for each session across groups. The table also displays average nap length and the average delay between familiarisation and nap onset in the Nap group.

Welch two-sample t-tests were conducted to check the presence of significant differences between groups in terms of age, delay length between familiarisation and Test 1 and time of day at which each session took place. Age was not significantly different between groups (t(43) = -0.82, p = 0.42). The delay length was statistically longer for the Nap than the Wake group (t(40.9) = 2.19, p = 0.04). The time of day at which each of the three calls happened did not differ statistically between groups (familiarisation: t(40.8) = -0.69, p = 0.49; post-delay test: t(40.4) = -0.18, p = 0.85; post-24h test: t(42.7) = -0.82, p = 0.42).

Group	Average general fam-	Average fam-nov at	Average fam-nov at

	nov (sd)	post-delay test (sd)	post-24h test (sd)
Nap group	0.28 (0.21)	0.22 (0.14)	0.34 (0.24)
Wake group	0.29 (0.25)	0.32 (0.29)	0.25 (0.20)

Table 3. Average recognition performance at each of the tests by group. Chance performance is 0.0.

Table 3 reports the average difference of looks to the familiar and novel words (hereafter, *fam-nov*) in each group, regardless of the testing session as well as separately for each testing session. A descriptive representation of the average memory performance of infants in each group at each testing session is shown in Figure 2.

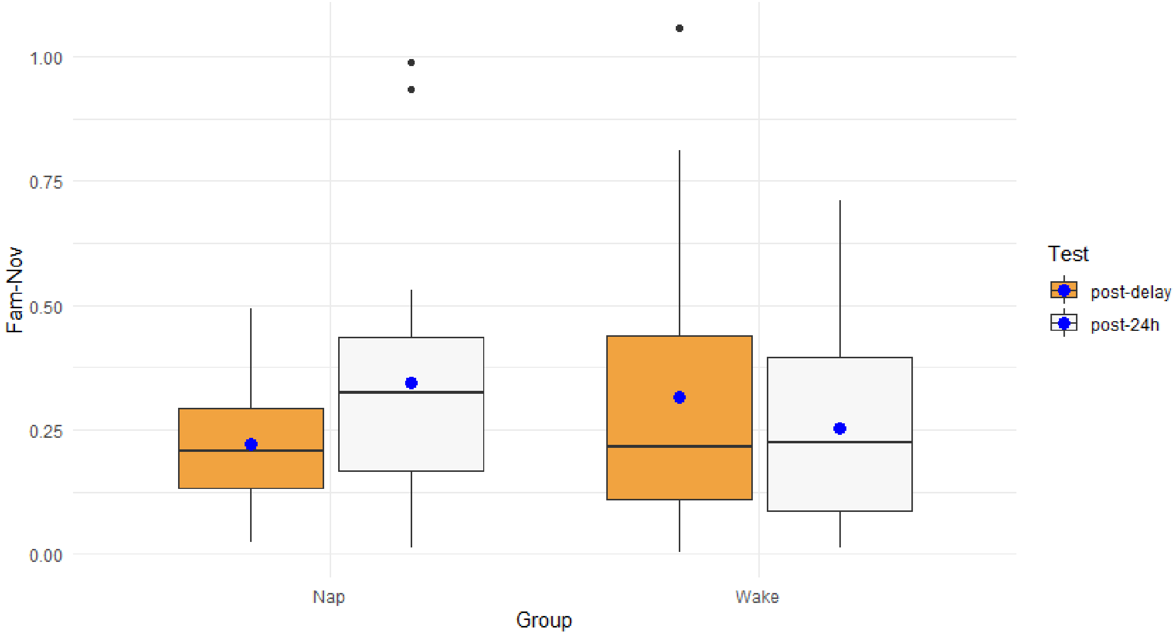

Figure 2. Average recognition performance at each of the two tests by Group. Chance performance is 0.0. The boxplot shows the median as a horizontal line across each box. The blue filled circle inside each box represents the mean.

Statistical analysis was run in R (R Core Team, 2015). We conducted linear mixed effects regression models (hereafter lmer) using the *lme4* package (Bates et al., 2015). P-values were calculated via likelihood ratio model comparisons tests using the *anova* function in R. This method quantified the relative influence of each predictor variable on the magnitude of the difference between looks to the familiar and novel words (*fam-nov*). In our model, *fam-nov* constituted our dependent variable, with *group* (Nap vs. Wake), *session* (post-delay vs. post-24h test), *fam word pair* (the familiarised word pair, i.e., poblet-gosset, duffin-taplin or kangle-bizzle) and *age* as fixed effects predictor variables. As the length of the delay between familiarisation and the post-delay test (henceforth, *delay*) is systematic according to group, group and delay length are inevitably correlated. For this reason, delay length is not included in the model, but its effects on generalisation will be analysed separately in the control group (i.e., the Wake group) (see below, and Figure 5). Among the fixed effects we also included the interaction between group and session, based on previous research that identified nap effects on memory not immediately after the nap but specifically at a test performed 24h later, following nocturnal sleep (e.g., Werchan et al., 2021). As the experiment involved repeated measures across multiple participants and the stimuli were uttered by multiple speakers, *participant* and *speaker* were also included in the model as random effects. Table 4 reports the results of the model comparisons testing for significant effects of each predictor variable.

Variables	**Chisq**	**Df**	**p**
group*session	**4.462**	**1**	**0.03466***
group	0.3901	1	0.5322
session	0.5664	1	0.4517
age	2.3196	1	0.1278
fam word pair	1.2699	1	0.2598

Table 4. Effects of predictor variables on the looking time difference to familiar and novel words (i.e., word recognition). Significant effects are displayed in **bold.**

None of the predictor variables contributed to *fam-nov* in a significant way, when considered individually. However, the interaction between group and session had a significant effect on *fam-nov*. The interaction is represented in Figure 3.

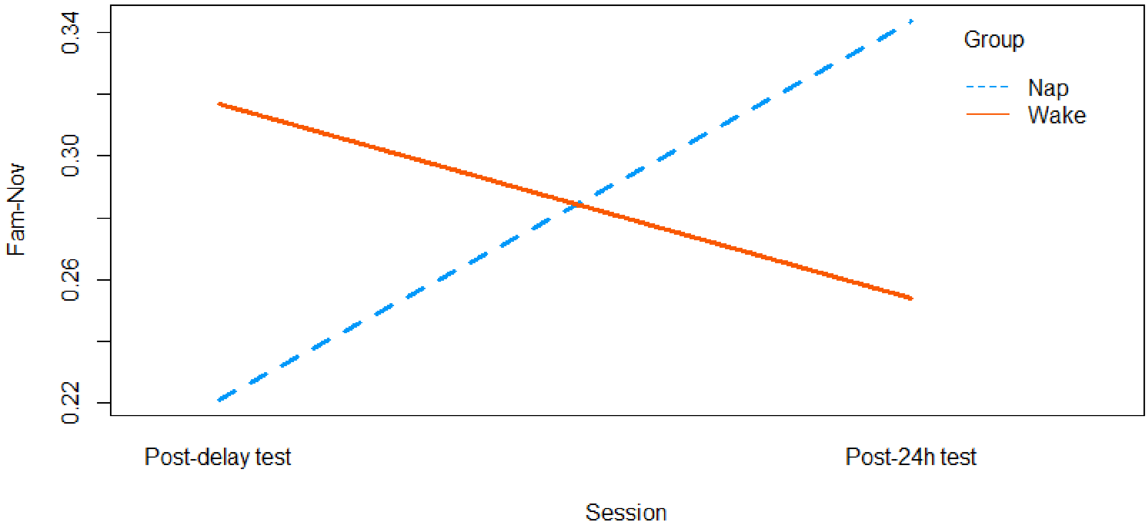

Figure 3. Interaction between session and group.

As mentioned above, *delay* was not included in the main analysis given its collinearity with the variable *group*. Nevertheless, its effects on word form generalisation were investigated separately in the Wake group (our control group). Figure 4 plots *fam-nov* relative to *delay* in the Wake group.

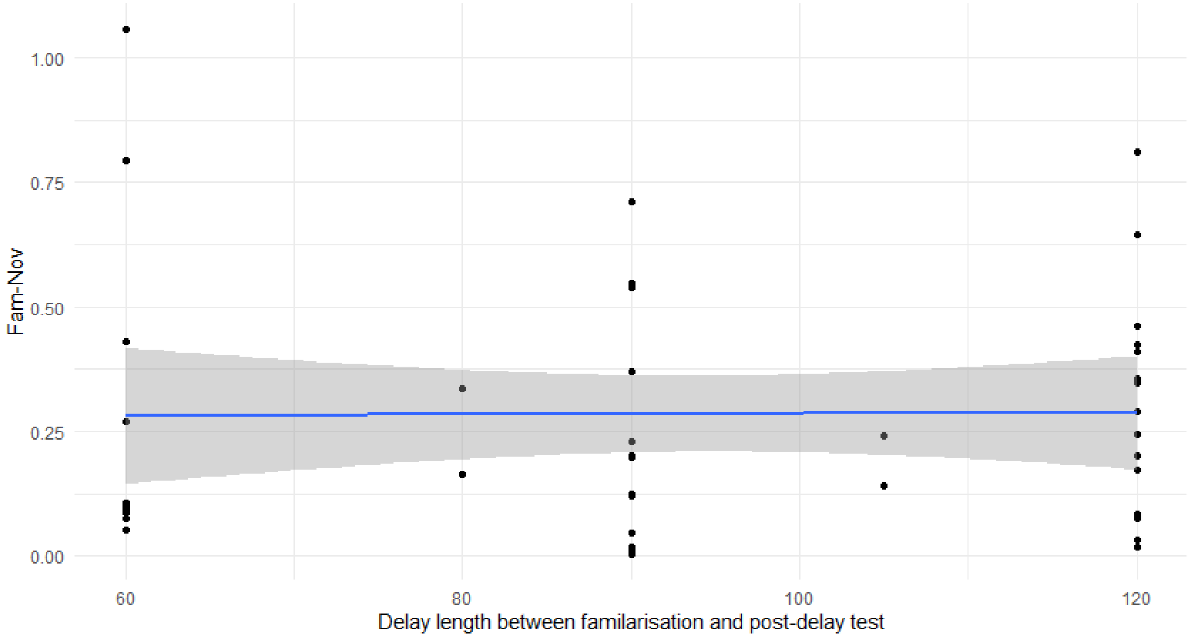

Figure 4. Word form generalisation performance relative to delay length in the Wake group.

Figure 4 shows a weak relationship between the two variables. Another model was run to test the significance of the *delay* predictor on *fam-nov* in the Wake group (see table 5).

Variables	**Chisq**	**Df**	**p**
delay	0.1051	1	0.75

Table 5. Effects of delay on the looking time difference to familiar and novel words (i.e., word recognition) in the Wake group. Significant effects are displayed in **bold.**

Delay did not significantly contribute to the Wake's group *fam-nov*. Therefore, although the Nap and the Wake group had significantly different *delay* values, that variable is unlikely to predict any between-group differences in *fam-nov.*

Second analysis: Nap characteristics

As outlined in the background section, there is evidence supporting effects of nap length and proximity of the nap onset relative to the learning episode on several forms of memory generalisation. Therefore, we conducted a similar analysis on our sample of nappers, to assess the influence of the duration of the nap, and that of the duration of the delay between nap onset and first exposure to the words, on *fam-nov*. Three participants were excluded from the Nap group at this stage because of missing or inaccurate information about their post-encoding nap.

Figure 5 and 6 represent the relationship between *fam-nov* and, respectively, the duration of the nap and the duration of the delay between first exposure to the words and nap onset.

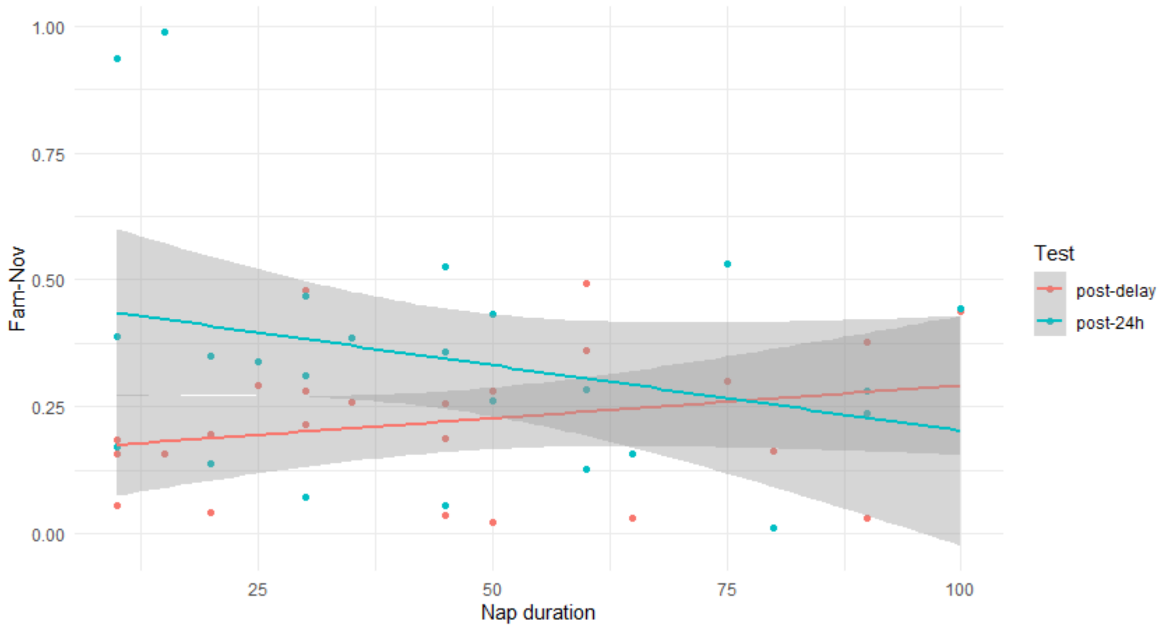

Figure 5. The relationship between word form generalisation and nap duration (in minutes).

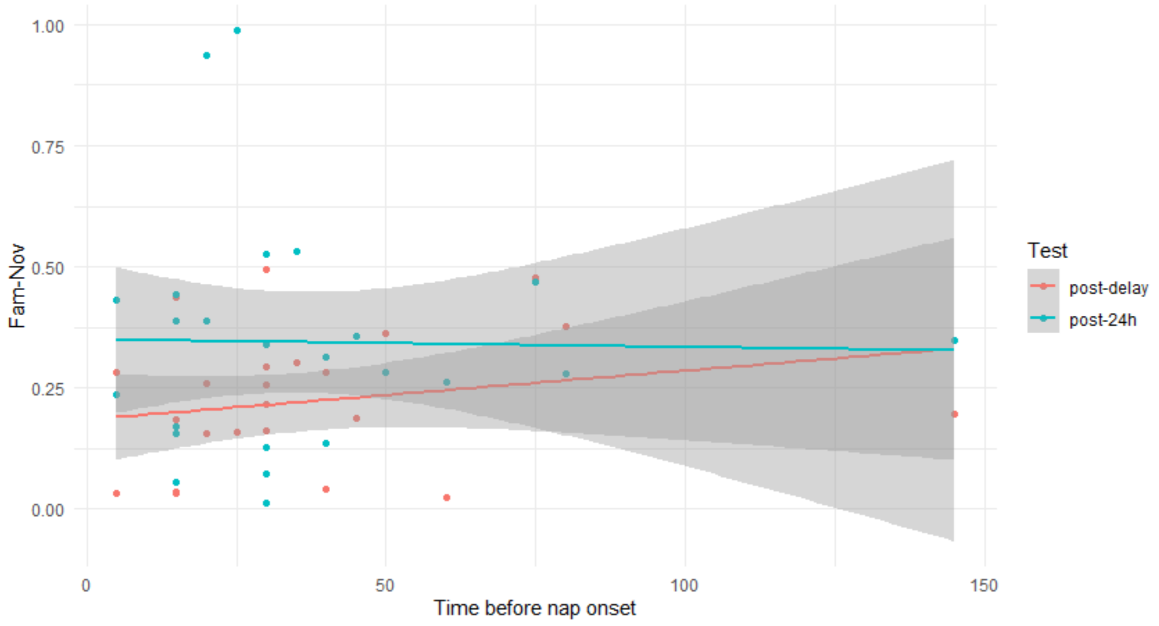

Figure 6. Relationship between word form generalisation and the post-learning delay before nap onset (in minutes).

Again, we conducted linear mixed effects regression models using the *lme4* package (Bates et al., 2015), with fam-nov as our dependent variable. This time, session (Post-delay vs. post-24h test), age, nap duration and nap onset delay constituted the fixed effects predictor variables. As the experiment involved repeated measures across multiple participants and the stimuli were uttered by multiple speakers, *participant* and *speaker* were also included in the model as random effects. Table 6 shows the results of the model comparisons.

Variables	Chisq	Df	p
Nap onset delay	0.029	1	0.8647
Nap duration	0.0377	1	0.8461
Age	15.95	1	0.4566
Session	**6.4465**	**1**	**0.0111***
Nap duration*Session	**5.185**	**1**	**0.02278***

Table 6. Effects of predictor variables on the looking time difference to familiar and novel words (i.e., word recognition) in the nap group. Significant effects are displayed in **bold.**

Session (i.e., post-delay test vs. post-24h test) had a significant effect on the dependent variable. This result confirms the findings reported in the main analysis. In addition, the interaction between nap duration and session was significant, as also suggested by Figure 5. In this Figure, two participants performed considerably above the mean at the post-24h test. We conducted an additional analysis to check whether the inclination of the regression line indicating performance at the post-24h test in Figure 5 could depend on these two data points being outliers. Rosner's test for outliers was conducted to assess the presence of any outliers in the Nap group sample. Three outliers were identified, two in the distribution of *fam-nov* scores and one in the distribution of nap length. After removing the corresponding datapoints, we plotted the relationship between nap duration and *fam-nov* again (see Figure 7).

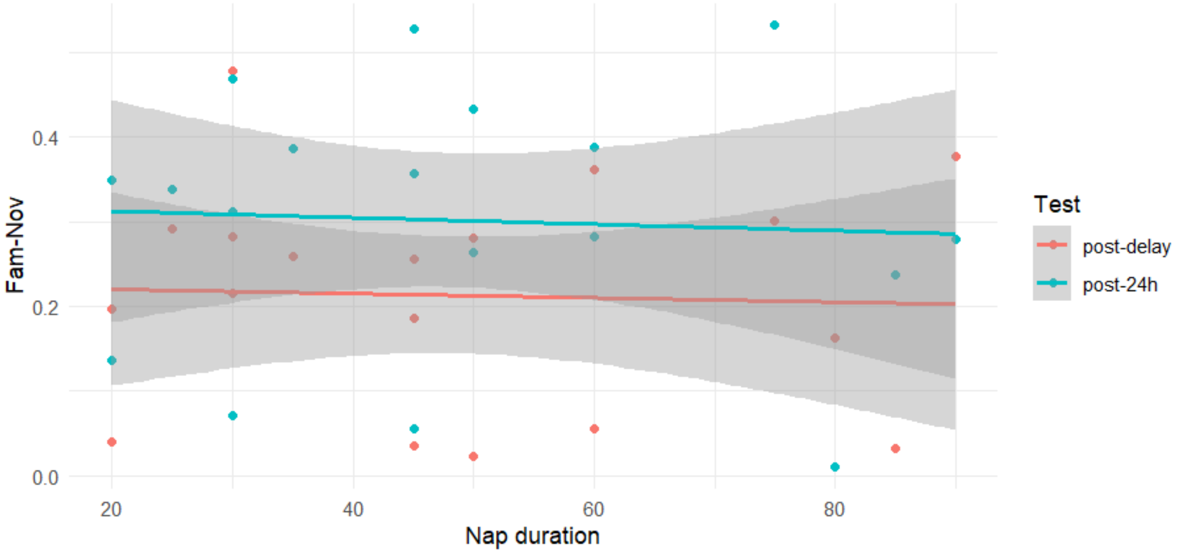

Figure 7. The relationship between word form generalisation and nap duration (in minutes), after removing the outliers.

We conducted the analyses again to check for any changes in the results following the removal of the outliers. The results are shown on Table 7. It is clear from Figure 7 that no interaction between nap duration and *fam-nov* exists after removing the outliers, so nap duration*session is not included in the model.

Variables	**Chisq**	**Df**	**p**
Nap onset delay	0.361	1	0.5479
Nap duration	0.0262	1	0.8714
Age	0.3481	1	0.5552
Session	**5.9459**	**1**	**0.01475***

Table 7. Effects of predictor variables on the looking time difference to familiar and novel words (i.e., word recognition) in the nap group, after removing the outliers. Significant effects are displayed in **bold.**

The only significant predictor was session, which confirms the findings of the main analysis. No other predictor was significant.

Additional exploratory analysis

Following up from our results, we conducted an exploratory analysis to check whether the use of absolute values of the difference between the mean z-scores of looks to familiar and to novel words was merited. We asked whether either group showed a systematic preference for the familiar or novel stimuli in either of the tests. To test this, we ran our analyses again but employed raw values of the difference between mean z-scores of looks to familiar and to novel words, not absolute ones. Table 7 reports the average of the raw values of the difference of z-scores of looks to the familiar and to novel words, per group, at each test.

Group	**average fam-nov (raw values) at post-delay test (sd)**	**average fam-nov (raw values) at post-24h test (sd)**
Nap group	0.08 (0.25)	-0.09 (0.40)
Wake group	-0.03 (0.42)	-0.04 (0.33)

Table 8. Average recognition performance at each of the tests by group. Significant effects are displayed in **bold**.

Figure 8 represents the infant memory performance in each group at each test with the raw values of the *fam-nov* difference as independent variable.

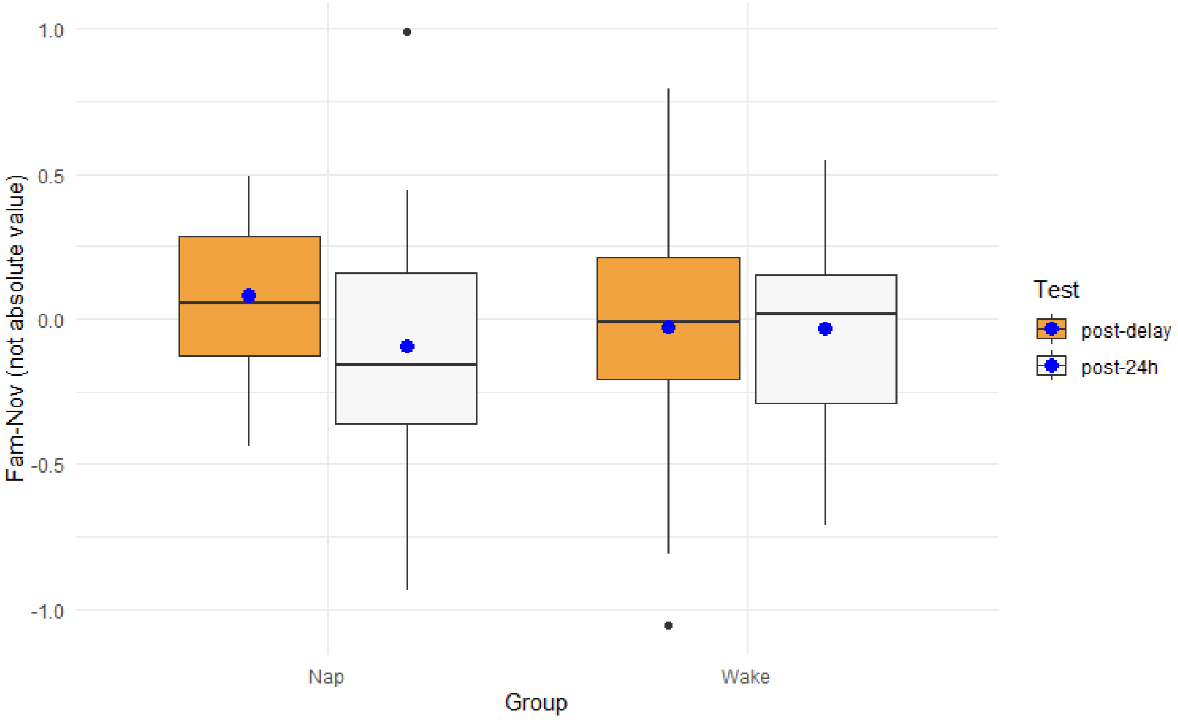

Figure 8. Average recognition performance at each of the two tests by Group. Chance performance is 0.0. The boxplot shows the median as a horizontal line across each box. The blue filled circle inside each box represents the mean.

Figure 8 shows a tendency towards a preference for the novel words (novelty preference) in the Nap group at the post-24h test, whereas the average preferences of the Wake group at both testing sessions and of the Nap group at the post-delay test are closer to 0.

We conducted a linear mixed effects regression model (hereafter lmer) using the lme4 package (Bates et al., 2015). P-values were calculated via likelihood ratio model comparison tests using the anova function in R. Again, this method quantified the relative influence of each predictor variable on the magnitude of the difference between looks to the familiar and novel words (fam-nov). In this model, the raw values of the fam-nov difference constituted our dependent variable, with group, session, fam word pair, age and group*session as fixed effects predictor variables. Again, *participant* and *speaker* were included in the model as random effects. Table 8 reports the results of the model comparisons testing for significant effects of each predictor variable.

Variables	**Chisq**	**Df**	**p**
group*session	1.4832	1	0.2233

group	0.165	1	0.6846
session	0.165	1	0.684
age	0.4089	1	0.5225
fam word pair	4.8321	1	0.082

Table 9. Effects of predictor variables on the looking time difference to familiar and novel words (i.e., word recognition). Significant effects are displayed in bold.

None of the predictor variables affected the difference between the mean z-scores of looks to familiar and to novel words, when this was not expressed in absolute values. Adopting absolute scores was then justified, as it made it possible to capture infants' ability to distinguish between familiar and unfamiliar nonwords, regardless of whether this ability was shown through longer looks to the familiar or the unfamiliar stimuli.

Discussion

We investigated the effects of a daytime nap and nocturnal sleep on 8-month-olds' ability to generalise the phonological form of newly learned words across different speaker's voices, i.e., across auditory differences. Previous experimental research on this ability revealed that similarly aged infants do not generalise across different-sex voices immediately after familiarisation; one day after familiarisation, 10-month-olds also fail to do so and cannot even generalise between same-sex voices. However, when primed by passages produced in the same voice they heard during familiarisation, infants as young as 7.5 months were able to generalise across same-sex voices one day after familiarisation (see Houston & Juszcyk, 2000; 2003). These studies were conducted without taking into account the role of sleep in memory generalisation. We aimed to shed more light on the factors that contribute to memory generalisation for phonological information contained in newly learned words.

Based on existing evidence of the beneficial effects on infant memory generalisation of a single nap, we expected to see between-group differences in word form generalisation already after a delay inclusive of a nap (Nap group), but not after a similarly long wake delay (Wake group). A second prediction was based on studies in which generalisation was observed after a combination of nap and nocturnal sleep: group differences would emerge after a delay but only on a second test on the next day, i.e., after night-time sleep, and generalisation would be observed only in infants who also had a nap after familiarisation. The third possible outcome of this study was that word form generalisation was exclusively supported by nocturnal sleep; in this scenario, word form generalisation would be observed in both groups, but only at the post-24h test. Furthermore, we investigated whether the length of the nap and the length of the delay between familiarisation and nap onset affected memory generalisation, as observed in other studies.

Our results supported the second hypothesis: it is the combination of daytime and night-time sleep that promotes word form generalisation in infants. While performance in the Wake group remained the same, the Nap group significantly outperformed their first responses on the second memory test, 24h after familiarisation, while the Wake group decreased their performance. This result indicates that night-time sleep, in combination with a daytime nap that happens shortly after encoding, significantly promotes infant generalisation of the phonological information contained in newly learned words. We found a significant effect of nap length, but no effects of the length of the pre-nap delay, on word form generalisation. As mentioned in the Results section, the presence of outliers has influenced the distribution of the data. Therefore, the significant effect of nap length should be interpreted with caution. As anticipated in the Methods section, the sample size that we were able to test was relatively small. This could have limited the power of our statistical analysis to detect any effects of pre-nap delay in the Nap group.

To our knowledge, this is the first study to investigate the effects of sleep on the generalisation of new word forms in infancy. It therefore contributes to a more complete understanding of memory generalisation in word learning, confirming previous evidence on the positive effects of the combination of nocturnal and diurnal sleep in many forms of memory generalisation in infancy (e.g., Hupbach et al., 2009; Sandoval et al., 2017; Werchan et al., 2021). Whilst not involving speech segmentation and thus employing an easier experimental task than the original studies (Houston & Jusczyk, 2000, 2003), this study also found evidence of word form recognition across different voices without priming in 8-month-olds, an age when this ability is still fragile (Houston & Jusczyk, 2000, 2003).

The differences in performance between the Nap and the Wake group could also have depended on circadian effects, had the familiarisation and/or testing phases happened at different times of the day across groups. However, the timing of the familiarisation and testing sessions did not statistically differ between groups. Alternatively, it could be argued that the two groups differed in their levels of alertness at encoding. However, the infants in the Wake group were not deprived of sleep; instead, their first two sessions were scheduled around times at which they were unlikely to nap. The parents were invited to do what they normally would have done during the delay between familiarisation and the post-delay test, and to respond to their child's needs as usual (including allowing them to nap). Then, before the post-delay test, they were asked whether their child had napped or not during the delay, and if they had napped, to say for how long and indicate the approximate awakening time (these measures allowed us to infer the nap onset time and the familiarisation-nap onset delay). Any infants in the Nap group who unexpectedly remained awake during the delay, and any infants in the Wake group who unexpectedly napped, were removed from the analysis. Interestingly, although encoding of new information for infants in the Nap group happened before their nap time, i.e., at a time when they were likely to be less alert and more tired than infants in the Wake group, they still exceeded their earlier performance, and that of the Wake group, following a night’s sleep. Furthermore, children who showed signs of fussiness or inattention at any of the sessions were discarded from the sample; thus, differences in affective state are unlikely to explain our findings.

What most likely accounts for the improvement in word form generalisation observed in the Nap group is the occurrence of a nap shortly following learning, in addition to the night’s sleep. A nap alone was insufficient to promote word form generalisation in the infants we studied. It is also unlikely that a night’s sleep alone can explain our results; if nocturnal sleep individually supported generalisation, we would have expected both groups to show comparable memory improvement at the post-24h test, but such an improvement was only observed in the group who had a post-encoding nap. It is also important to note that some infants in the Wake group may have taken naps that we did not detect, specifically between the post-delay and the post-24h test. So, those infants may still have had a post-encoding nap, although much later and at more variable delays after encoding than the Nap group (who napped within the retention period). This means that some infants in the Wake group may also have had opportunities, during that later nap, to generalise the new information acquired in familiarisation, which could also have been reinforced in the post-delay test. This could explain the larger variability in word form generalisation performance in the Wake group, as shown in Figure 2. However, the systematic increase in performance across memory tests observed exclusively in the Nap group suggests that napping shortly after learning and nocturnal sleep represent the best combination for generalisation of new phonological information. Nevertheless, future studies could provide a more detailed picture by monitoring the nap and sleep schedules of both Nap and Wake groups across multiple testing sessions and assessing the effects of the number and timing of naps on the generalisation of new linguistic information.

In this regard, Mason et al. (2021) found, in their pioneering study assessing the relative benefits for memory of morning and afternoon naps, that 9-month-olds' performance in an imitation memory task learned in the morning was better following both a post-encoding morning and afternoon nap, and that skipping the post-encoding morning nap was detrimental to memory, even when memory performance was tested after the afternoon nap. Furthermore, while Slow Wave Activity (SWA) in the afternoon nap was associated (albeit weakly) with better post-afternoon nap memory performance when infants also took a morning nap, SWA in the afternoon nap and post-nap memory performance were negatively associated when the morning nap was missed. This finding may not necessarily mean that SWA during the post-encoding nap impaired consolidation. Rather, it could mean that infants who suffered the most from missing their morning nap experienced stronger SWA in their afternoon nap in compensation and also performed poorly in the behavioural test following the afternoon nap.

The evidence from Mason et al. (2021) points to the differential contribution of post-learning morning and afternoon naps to imitation memory at 9 months of age, a slightly older age than the average in our study. Two-thirds of the infants in our Nap group had their post-encoding nap in the morning (i.e., before 12:00) (n = 16). Our study measured a different kind of memory from Mason et al. (2021) and assessed memory generalisation rather than consolidation. However, if morning naps were particularly beneficial for infants in our study, as observed in Mason et al. (2021), this would support two interpretations of our findings: a) the advantage in word form generalisation observed in the Nap group could have been boosted by most of the group taking their post-encoding nap earlier in the day and b) as the timing of familiarisation and post-delay test did not significantly differ across groups, the advantage of the Nap group over the Wake group could have been inflated because of the Wake group missing their morning nap. Contrary to Mason et al. (2021), where infants were kept awake in the morning to test the effects of missing the morning nap, we invited the parents to do what they would normally do with their children during the delay between familiarisation and post-delay test, suggesting neither that they keep their child awake nor that they encourage sleep. So it is unlikely that the Wake group's performance at the second test could be explained by their skipping their morning nap. Nevertheless, as we are ignorant as to when or how often our participants napped over the 24 hours spanned by the experiment as a whole, we cannot estimate whether the occurrence or non-occurrence of further consolidation opportunities could explain variance in the Nap or Wake groups' performance. To develop a full picture of the influence of polyphasic sleep on memory generalisation in infancy, additional studies could develop a design comparing infants' performance when their post-encoding nap occurs in the morning vs. in the afternoon, and before vs. after nocturnal sleep.

Our results raise other issues that should be addressed in future research. The combination of daytime and nocturnal sleep might be necessary for memory consolidation in early childhood given the prolonged maturation of the memory system (Mullally & Maguire, 2014; Jabès & Nelson, 2015). In this context, naps may serve as important additional opportunities to initiate consolidation of new memories and their connections when the memory system is still immature, protecting them from interference (Mullally & Maguire, 2014). Consequently, letting go of naps has been theorised to be associated with the maturation of the memory system in children, as it necessitates maintaining information acquired during the day long enough for it to be consolidated during nocturnal sleep (Lam et al., 2011; Kurdziel et al., 2013; Esterline & Gómez, 2021). It therefore remains an open question whether we can observe similar effects of sleep on word form generalisation in older children, who no longer nap habitually. To shed light on this issue, future research could employ a between-subject design comparing word form generalisation performance in age-matched habitually and non-habitually napping children, after a delay spent awake and one inclusive of a daytime nap. It could be a challenge to convince children who no longer nap to do so, but online data collection would lend itself well to this design, as it would allow the children and their families to take part in the study in a more familiar environment and thus reduce the sense of novelty and stimulation potentially associated with the experimental setting, which could interact with falling asleep.

We investigated a form of memory generalisation, i.e., the phenomenon by which new information goes beyond retention and is integrated into networks of related memories, based on the implicit extraction of regularities across new and existing memories (Landmann et al., 2014; Walker & Stickgold, 2006). Whether sleep and, specifically, the combination of a nap and night-time sleep would also have supported infants' memory for the specific items presented in familiarisation (i.e., words in the original voice) remains an open question. Retention of specific memories results from the stabilisation of those memories acquired at encoding; although the exact timeline of memory stabilisation and generalisation remains unclear, memory generalisation has not usually been observed independently of stabilisation (Stickgold & Walker, 2013). In addition, it has been suggested that memory generalisation might be temporarily inhibited during a post-encoding nap, in order for veridical memories of the new information to be formed first (Friedrich et al., 2020). Although, based on this evidence, we could have expected sleep to support veridical memory for the new word forms as it did their generalisation, the relative role of the nap and night-time sleep might have been different for veridical memory, with a single nap potentially supporting the stabilisation of the encoded phonological forms. Future studies investigating both the stabilisation and the generalisation of newly learned word forms could shed more light on the consolidation of newly learned phonological memories in infants.

Our design did not include a generalisation test immediately after familiarisation. Immediate tests can provide valuable information about the quality of the initial encoding of new information, thus enabling researchers to follow the process of consolidation of the newly learned information more clearly. Although the levels of alertness and affective state did not seem to differ across groups, and the two groups showed similar levels of performance at the first test (suggesting that they had encoded the new information at comparable levels), we cannot be absolutely certain that encoding capacity was comparable between the two groups. Conducting multiple tests with infants is problematic, due to their relatively short attention span compared to adult participants. However, the introduction of immediate tests is recommended to rule out the possibility of prior differences in encoding capacities between groups. A related issue is the role of *prior* sleep for encoding of new information (Seehagen et al., 2019). There is abundant evidence that sleep deprivation prior to learning impairs memory encoding in adults (e.g., Yoo et al., 2007). In infants, higher quality sleep in the night prior to participating in an imitation task correlated with better encoding in the subsequent task (Konrad, Herbert et al., 2016), and memory performance is associated with patterns of daytime and night-time sleep even over the entire week prior to participation (Lukowski & Milojevitch, 2013). Assessing the quality of sleep both before and after the experiment, via parental reports, polysomnography or sleep actigraphy, for example, could improve the interpretation of findings in future studies.

Our last remark is methodological and concerns the method of data collection employed in our study. We collected data online, by adapting a typical lab procedure. This means that the experiment took place in a considerably less well-controlled environment (i.e., the participant’s home), and that the quality of the collected data depended greatly on caregivers and their technological devices. Although these factors potentially reduce the replicability of our findings, collecting data online also brings a number of advantages. The home environment constitutes a more naturalistic environment compared to the developmental lab and better corresponds to the infant's everyday learning conditions, increasing the ecological validity of our data. Online data collection could be particularly useful in infant sleep research, as it allows researchers to examine the effects of sleep on memory without interfering with the infant’s nap and sleep routines.

Conclusion

The literature has found a strong relationship between sleep and several aspects of word learning in infancy (see Belia et al., 2022). Existing studies provided no evidence bearing on the effects of sleep on the generalisation of new phonological information contained in novel words. This ability, which we call word form generalisation, is crucial to communication, as it underlies the ability to recognise words across different auditory exemplars, produced by either a single speaker or multiple speakers. Ultimately, word form generalisation entails the extraction of auditory regularities across multiple auditory instances of the same word and the construction of a generalised phonological representation for that word. This defines it as a memory generalisation process, which therefore could be supported by sleep.

In this first comprehensive assessment of the effects of sleep on infant word form generalisation in infancy, we identified a complementary effect of naps and nocturnal sleep. Specifically, the benefits of nocturnal sleep for memory generalisation were seen only for the infants who had taken a nap. These findings complement those of earlier studies that observed the combined effect of naps and night-time sleep on other forms of memory generalisation in language learning (e.g., Werchan et al., 2021). Therefore, these findings support and extend existing research on sleep-associated memory generalisation in infants, which has been mainly studied in relation to the generalisation of new word meanings (e.g., Friedrich et al., 2020) and the extraction of the underlying structure in a continuous string of stimuli (Gómez et al., 2006; Hupbach et al., 2009).

The findings of this study contribute to our understanding of the relative role of naps and nocturnal sleep for the acquisition of linguistic information in early childhood and provide theoretical as well as methodological bases for studying this ability further.

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*The description of the candidate and co-authors contribution to the publication may be framed in a manner appropriate to the area of research but should always include reference to key elements (e.g. for laboratory-based research this might include formulation of ideas, design of methodology, experimental work, data analysis and presentation, writing). Candidates and co-authors may find it helpful to consider the CRediT (Contributor Roles Taxonomy) approach to recognising individual author contributions.

Paper 3. Exploring developmental connections: Sleep patterns, self-locomotion, and vocabulary growth in early childhood.

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Abstract

Current research indicates that there are likely developmental connections between the evolution of sleep patterns, motor skills progression, and the expansion of vocabulary. These connections are grounded in the well-established role of sleep in memory and learning, as well as in the cascading effects on language development of the acquisition of new motor skills. However, no study has so far undertaken a comprehensive and systematic examination of these connections or explored their developmental trajectory over time. Yet understanding vocabulary development depends on considering development in the sleep regulation and motor domains, to provide a biologically grounded explanation of how early lexicons are built and strengthened. This investigates the links between vocabulary growth and two distinct moments of significant transformations over the first two years of life: self-initiated locomotion and the regulation of sleep patterns. Our results reveal nonlinear associations between these domains. These associations were found to emerge at ages of marked developmental change. Our findings point towards the importance of investigating vocabulary development from a dynamic systems perspective, as the product of continuous and dynamic interactions between cognition, the body and the environment.

Introduction

Infancy is a period of outstanding plasticity, where small changes in one domain can have broad and significant long-term consequences (Karmiloff-Smith, 1998); studying domains individually carries the risk of missing crucial associations and ‘decontextualising the child’ (Scholnick, 2001). From a biological perspective development is best treated as a holistic phenomenon at both individual and global timescales (see Thelen and Smith, 1994).

The indissoluble relationship between cognition and biology in development is indisputable: Cognition is inherently tied to biology, because it is embodied in the living organism. Consequently, language development should be studied in the context of a body that is growing and developing in the ways it moves and interacts with its surroundings (Iverson & Thelen, 1999; Iverson et al., 2010). Furthermore, language development should be studied in relation to the biological processes that underlie learning, memory and cognitive function. Sleep has a fundamental role in these processes (see Rasch & Born, 2013), and emerges as a distinctive feature of infant life, with newborns spending a significant portion of their time asleep. As sleep patterns evolve dramatically during child development, their interplay with learning and memory can have cascading effects on language and other developmental processes.

In alignment with this holistic perspective on infant development, our longitudinal investigation examines the interplay between sleep patterns, vocabulary acquisition, and self-initiated locomotion during the first two years of life. Recognising the indissoluble connection between cognition and biology, this study examines vocabulary learning as deeply rooted in the processes shaping an evolving body, and as intimately linked to the memory mechanisms influenced by sleep. Intriguingly, several studies have found reciprocal relationships between vocabulary development and both motor skill and sleep patterns. However, no study has systematically and longitudinally explored these relationships collectively over time. Our research addresses this gap by integrating domains that were previously studied independently. Specifically, we examine how the associations between vocabulary development and two highly dynamic domains, namely self-initiated locomotion and the regulation of sleep patterns, unfold during the initial two years of life.

Sleep regulation

Sleep is an essential biological function that undergoes radical changes over the childhood period, particularly over the first two years of life. These changes are driven by the interplay of environmental factors, the development of self-regulatory mechanisms and physiological maturation (France et al., 1999). This makes them subject to significant inter- and intra-individual variability. Nevertheless, recurrent phenomena can be observed in the development of sleep patterns, characterised by a gradual shift to predominantly long uninterrupted sleep at night as the child develops the ability to self-soothe (Paavonen et al., 2020). One should note that expectations around child sleep development are culture-dependent (Owens, 2004). Although 'sleeping through the night' is commonly considered the landmark of sleep maturation in Western cultures, this is not the case in cultures where polyphasic sleep is more common even among adults (see Jeon et al. 2021; Owens, 2004). Thus what is generally believed to be developmentally appropriate within the field of sleep regulation is culturally defined. As this study has been run in the UK, with the data collected from infants and toddlers based in the UK, it will follow the research literature surrounding sleep regulation and infant development relevant to this population. However, research comparing the development of sleep patterns across culturally different populations is needed to better determine the effects of sleep regulation on infant development.

Some general tendencies can be found in sleep regulation in infancy. Overall time spent asleep across 24 hours decreases progressively, with newborns sleeping up to 20 hours a day and gradually decreasing their sleep time to 13 hours on average between 6 and 12 months of age and to 12 hours by the beginning of the second year of life (see Galland et al., 2012). The number of night awakenings progressively decreases too, as does the ratio of daytime over night-time sleep duration, with less sleep gradually happening during the day than at night (Galland et al., 2012; Iglowstein et al., 2003). In other words, nocturnal sleep gradually consolidates, following fewer awakenings and fewer hours spent napping during the day (Iglowstein et al., 2003). Immediately after birth sleep tends to be markedly polyphasic, organised in multiple short bouts distributed over the twenty-four hours. It gradually stabilises into three phases (morning nap, afternoon nap and night-time sleep) by around 6-12 months of age (Weissbluth, 1995). After that daytime napping decreases from two naps to one at around 15-18 months (Galland et al., 2012) and usually ceases between 3-5 years of age (Staton et al., 2020).

The importance of naps at earlier ages is corroborated by findings such as those from Mason et al. (2021), who observed the importance of two naps for optimal consolidation of newly learned information at 9 months of age. However, the benefits of napping at later ages are less clear. A systematic review found that longer and more numerous naps during the day are associated with shorter and/or more more disrupted night sleep after the second birthday, suggesting that, while napping is an integral component of sleep patterns in the first two years of life, its integration into sleep patterns might become less optimal afterwards (Thorpe et al., 2015). Other studies have found that naps benefitted memory consolidation regardless of age. In these studies, children as old as 4 years still benefited from daytime naps in consolidating spatial memories and novel words, but only if they were still habitually taking naps (Kurdziel et al., 2013; Esterline & Gómez, 2021).

Sleep regulation and development

Infant sleep habits are associated with development in a wide array of domains, affecting both cognition (e.g., memory, language, executive function) and physical wellbeing (e.g., bodyweight) (Tham et al., 2017). In an actigraphy study, Scher (2005) reported slower general development in 10-month-olds with more fragmented sleep and greater motor activity during sleep. Sleep efficiency (i.e., the time actually spent asleep over the total hours of bedtime) was positively associated with developmental scores. After controlling for age and gender, higher proportions of nocturnal sleep relative to daytime sleep were associated with higher scores in cognitive and motor development (Gibson et al., 2011). Both at 18 months and 4 years of age, a larger proportion of time spent asleep at night than in daytime naps was associated with more advanced executive functioning (Bernier et al. 2013; Bernier et al., 2010). However, it is worth noting that the relationship between sleep and development can exhibit some variability throughout the first year of life. For instance, in Pecora et al. (2022), 8-month-olds with longer daytime sleep exhibited higher cognitive development scores. In addition, less time spent asleep during the day and during the night at 4 months (but not 8 months) was positively associated with development of simple motor skills (e.g., lifting the head, reaching for objects) (Pecora et al., 2022).

Sleep patterns at early ages predict cognitive outcomes later in life. For example, Touchette et al. (2007) linked shorter sleep duration in early childhood with poorer cognitive performance and vocabulary knowledge at later ages. In Pisch et al. (2019), infants (aged 4, 8 and 10 months) who demonstrated more mature working memory at earlier ages also had less wake time during the night in the first months of life. However, the number of night awakenings, day and nocturnal sleep duration were not related to working memory performance. Slow Wave Activity (SWA), a typical electrophysiological phenomenon observed in the sleeping brain, improves the brain’s ability to encode new information during subsequent wakefulness (Van Der Werf et al., 2009; Antonenko et al., 2013). Thus, more uninterrupted sleep at night may ensure full SWA functioning; this would enhance the brain's ability to learn new information in the wake time that follows (Pisch et al., 2019). Studies have also revealed effects of sleep patterns on cognitive performance on a more local timescale. For example, Lukowski and Milojevitch (2013) found that 10-month-olds experiencing more night awakenings in the week prior to testing performed worse in a memory generalisation task, while the length of time spent in daytime naps in the week prior to testing was associated with better performance. The proportion of night sleep duration over total sleep in the week prior to testing was negatively associated with encoding and immediate recall, but no associations were found between this measure and delayed memory recall.

Sleep regulation and vocabulary development

Associations have been found between infant sleep patterns and vocabulary measures. For example, Lam et al. (2011), who tested preschoolers (3-5 years of age), found that time spent napping correlated negatively with receptive vocabulary and auditory attention span. As napping time correlated negatively with time spent asleep at night, the authors suggested that longer night-time sleep lessened the need for daytime napping and therefore contributed to neurocognitive performance. This study highlights the importance of night-time sleep for preschool children. Several studies have observed significant longitudinal associations between sleep patterns in early life and vocabulary growth, but the findings are mixed. Horváth and Plunkett (2016) found positive associations between the number of daytime naps taken between 8 and 38 months of age and receptive vocabulary (and marginally with productive vocabulary) measured 3-6 months after the assessment of sleep patterns. In addition, fewer hours spent asleep at night predicted a faster growth rate for productive vocabulary (Horváth and Plunkett, 2016). In contrast, other studies underline the importance of night-time sleep for preschool children. For example, Dionne et al. (2011) observed that the ratio between daytime and night-time sleep duration at 6 months predicted language outcomes at 18 and 30 months, with a smaller proportion of sleep happening during the night being associated with poorer subsequent language skills. Importantly, the children experiencing language delays at 60 months had been reported to sleep a smaller proportion of time at night between 6 and 18 months, and that relationship held even when level of language development at previous ages were controlled for (Dionne et al., 2011). These findings suggest that the daytime / night-time sleep ratio has a durable effect on language outcomes in the early years. Knowland et al. (2021) highlighted long-term associations between sleep patterns in the early years and vocabulary at school entry. Specifically, longer and less interrupted sleep at night than in the daytime between 6 and 36 months was associated with larger receptive vocabularies at school entry.

Although some of these findings are in conflict, they highlight local and long-term associations between sleep regulation and language outcomes in terms of lexical knowledge. However, the specific sleep parameters involved in the sleep regulation process have different implications for vocabulary knowledge. The evidence reviewed in this section is consistent with the well-established role of sleep and naps in new word learning (see Belia et al., 2022, and Axelsson et al., 2016, for reviews), which is accounted for by the memory consolidation and enhancement processes occurring during sleep (see McClelland et al., 1995, Born & Wilhelm, 2012; Rasch & Born, 2013; Stickgold & Walker, 2013; Lewis & Durrant, 2011; Davis & Gaskell, 2009). Infants napping shortly after exposure to novel words consistently remember those words better than infants who stayed awake during the same time frame, at various ages (e.g., Horváth & Plunkett, 2015; Axelsson et al., 2018; William & Horst, 2014). Napping after exposure to novel words not only supports memory for those words but enhances it. This is evidenced by the ability to generalise newly learned category labels to novel, previously unseen exemplars of the same object category (e.g., Friedrich et al., 2017) and by the ability to extract word forms from a string of nonwords in an artificial language (Gómez et al., 2006; Simon et al., 2017). For both forms of generalisation, napping shortly after learning was revealed to have long-lasting effects on generalisation performance 24h later (Werchan et al., 2021; Hupbach et al., 2009). In a recent study, napping shortly after exposure to novel word forms improved 8-month-olds' ability to recognise them in a novel voice (i.e., word form generalisation: Belia et al., under review). However, such an improvement was not evident immediately after the nap but only twenty-four hours later, when both a timely nap and nocturnal sleep had occurred after the infants' exposure to the words. These findings provide important insights into the role of naps in early vocabulary development.

Motor skill and vocabulary development

Although language and motor development might appear to be independent domains, many studies have found that they are interrelated. For example, the extent of gesture use (mainly pointing) to refer to objects at 18 months predicts vocabulary at 42 months (Rowe & Goldin-Meadow, 2009), perhaps due in part to parental use of labelling in response to pointing (Goldin-Meadow et al., 2007). The interconnectedness of language and motor systems is likely to be obtained long before infants produce words. Building upon evidence indicating the close relatedness of motor and language functions in the brain and the coordination of hand and mouth activity from birth (e.g., the Babkin reflex), Iverson and Thelen (1999) examine evidence supporting the idea that the rhythmic limb and torso movements commonly observed in infancy, such as waving, swaying and banging, coincide with the rhythmic jaw movements that, coupled with vocalisation, give rise to babbling behaviour. Through this co-activation, vocal and gestural behaviours entrain one another and eventually co-develop towards the precise coupling of words and gestures observed in adult communication (Iverson & Thelen, 1999). Motor development is connected to language development more globally as well, as shown by the cascading effects of motor attainments on infant communication and caregiver input (Campos et al., 2000). Mastering a new motor skill opens a new set of ways in which infants can perceive and act upon their environment. This shapes the level of linguistic input and output that infants receive from and direct to the environment. For example, the ability to sit unsupported frees infants to use their hands to explore objects. This enables them to appreciate the shape and texture of the objects. In addition, that development elicits new input from caregivers, who are more likely to label objects when these are held or manipulated by their infant (West & Iverson, 2017). The impact of all this can be seen in infants diagnosed with language delays or ASD. These infants typically show fragilities in language development and communication and are also slower in developing the gestures involved in object manipulation (West et al., 2020). This, in turn, reduces the extent to which caregivers respond with labels to object manipulation (Leezenbaum et al., 2014).

The onset of independent locomotion is particularly significant in this respect, as it enables infants to reach distant objects and explore the space around them autonomously; this has important implications for cognition and communication. The onset of crawling on hands and knees marks the onset of willing, autonomous, self-initiated locomotion and, as such, it has been referred to as the “psychological birth of the human infant” (Mahler et al., 1975, cited in Campos et al., 2000). Crawling also introduces important changes in the way infants perceive the world around them and is followed by dramatic changes in emotional, social, communicative and cognitive development (Campos et al., 2000). Among other things, crawling significantly increases the opportunities for social interactions, by introducing the need for distal communication and referencing. This increases the number of referents parents and children can label and refer to (Campos et al., 2000). Similarly, the transition to independent walking influences communicative advances. Independent walkers can carry objects with their hands and bring them to their caregivers; they do so more frequently than their crawling same-age peers (Karasik et al., 2014). An earlier onset of the ability to sit and walk predicted larger productive vocabulary growth in 16- to 28-month-olds (Oudgenoeg-Paz et al., 2012). Similarly, the onset of walking is associated with an increase in receptive and productive vocabulary, independently of age (Walle & Campos, 2014). Infants who walk independently vocalise more and spend longer periods of time interacting with their caregiver compared to their peers who walk with the aid of a walker (Clearfield, 2011). This suggests that independent locomotion specifically (and not the movement of the limbs involved in walking or the fact of moving upright through space per se) is associated with a stronger base for communication (Clearfield, 2011). This is mirrored in the results from the naturalistic observations of parent-child interactions in Walle and Campos (2014), where the level of linguistic input from the parent was significantly correlated with larger receptive and productive vocabularies in walking (but not crawling) infants. These findings suggest that level of motor skill and language input interact to shape further communicative development.

Sleep and motor skills

Several studies have demonstrated a bidirectional relationship between sleep parameters in infancy and motor development. In Scher and Cohen (2005), 5-8-month-olds who had started crawling had more night awakenings than their non-crawler peers, regardless of age. Specifically, the presence of crawling predicted 17% of night awakening variance. In an actigraphy study conducted by Scher (2005) with 8-month-olds, infants with higher motor scores who had already started crawling experienced more awakening episodes at night, longer sleep duration and higher levels of motor activity during sleep than non-crawling age peers. These findings provide evidence for an effect of the onset of crawling on sleep. This might be due to higher energy expenditures during the day in relation to more demanding motor activity, and to more intense emotional responses in caregiver and infant alike following the emergence of independent locomotion. These factors are likely to influence levels of arousal, tiredness and stress at bedtime (Scher & Cohen 2005).

A recent line of research links the higher sleep disturbance observed over the second half of the first year to the ‘twitches’, or rapid, isolated muscle movements, that characterise mammal sleep (Blumberg, 2015). Twitches are common in sleeping mammals at every age but are particularly prominent in infants, who spend a considerable amount of time asleep. The idea that they might contribute to the consolidation of sensorimotor information emerged two decades ago, when signals from twitching limbs in pup rats were found to activate areas in the primary somatosensory cortex (Khazipov et al., 2004). This led to the hypothesis that twitches could be spontaneous movements that drive the consolidation of the neural pathways involved in motor activity (Blumberg, 2015). In this theory, the sensory feedback produced during twitches ultimately consolidates goal-oriented wake movements (Blumberg et al., 2013). In a recent study, twitches have been found to be temporally associated with spindles during sleep, suggesting that they might be involved in the consolidation of motoric patterns (Sokoloff et al., 2021). These findings add a further level of complexity to the interplay between sleep, language and motor domains. If advances in motor development lead to more disturbed sleep, then the straightforward conclusion that less disturbed sleep and increasing motor skills are both associated with faster vocabulary development (or larger lexicons) would require some modification, given that sleep and motor development interact in complex ways.

This study

The lines of research summarised above recognise critical associations between self-locomotion and vocabulary, on the one hand, and sleep regulation and vocabulary, on the other. However, to date no studies have systematically examined these associations together. This study traces the development of sleep patterns, self-locomotion and vocabulary across the first two years of life. The aim is to understand the associations between shifts in sleep patterns, emergent self-locomotion and vocabulary development, while also investigating how these relationships change over time. The overarching goal of this investigation is to provide a biologically sound perspective on vocabulary development, considering vocabulary learning as a memory-based process and also as a product of the interactions between the body and the environment.

Methods

Participants

A total of 89 children were initially included in the study. However, some children were excluded due to families withdrawing from the study (*n*= 17) or missing two or more data collection points (*n* = 21). The final sample consisted of 51 children, 20 of whom started participating at seven months of age, contributing to four data points, while the rest joined at one year of age, contributing to three data points. Participants had no known hearing, vision or developmental problems. The children were based in the UK and exposed mainly to British English. Families were contacted through social media, existing participant databases and through the advertisement channels of other UK-based developmental laboratories.

Data were collected at ages 7 months (*n* = 20, range = 6;24 - 8;7, M= 7;8), 12 months (*n* = 51; range = 11;23-13;4, M=12;6), 16 months (*n* = 51, range = 14;28-16;26, M = 16;1) and 24 months (*n* = 51, range = 23;25 - 24;17, M = 24;8). The mean ages and ranges are based on the dates of completion of the first day of the sleep diary at each data collection point.

Procedure

We collected data about the children's sleep, vocabulary and motoric skills at every age, using three different questionnaires.

1. Children's sleep was assessed using an adaptation of the Sleep and Naps Oxford Research Inventory (SNORI) (Horváth & Plunkett, 2016). This is a paper diary where parents are asked to record their child's sleep behaviour over ten days. We shortened the diaries to five days, to limit participant attrition and facilitate compliance. On each day (over a 24-hour timeline) parents were asked to indicate the times when their child was asleep. They were also asked to note any night awakenings and where their child was sleeping (e.g., pushchair, car, cot). They were also asked to indicate any nursery days and any special events or conditions (e.g., severe illness, trips to countries in different time zones). Any sleep occurring between 8am and 6pm was considered daytime sleep. We considered a nap to be any parent-reported bout of sleep occurring during this time frame. Any sleep occurring between 6pm and 8am was considered nocturnal sleep (see Horváth & Plunkett, 2016).

Through the SNORI we collected the following data:

- Number of Naps (NN)
- Number of Night Awakenings (NNA)
- Proportion of sleep occurring at night vs. during the day (N/D). This was calculated as follows:

$$\frac{Nocturnal\ sleep\ duration\ -\ Daytime\ sleep\ duration}{Nocturnal\ sleep\ duration\ +\ Daytime\ sleep\ duration}$$

Thus N/D is a number between -1 and +1, with a value of -1 corresponding to sleep occurring exclusively between 8am and 6pm and +1 corresponding to sleep occurring exclusively between 6pm and 8am. A value of 0 would suggest equal time spent asleep during the day and during the night. N/D values closer to +1 suggest shorter time spent asleep during the day and/or longer time spent asleep during the night.

2. Children's vocabulary was assessed via an online version of the UK Communicative Development Inventory - Words and Gestures (CDI) (Alcock et al., 2020). This inventory is a checklist of words commonly acquired between 8 and 18 months. Parents are asked to indicate which words their children understand only and which ones they also say. Scores for receptive and productive vocabulary are derived by counting how many words the parent reported their child to understand and to both understand and say. Specifically, receptive vocabulary size is calculated as the sum of the 'understands' and 'understands and says' scores, whereas the productive vocabulary size corresponds to the 'understands and says' score alone.

3. Motoric skills were assessed via the Vineland Adaptive Behavior Scales (Motor Skill Domain) (Sparrow & Cicchetti, 1989). We used only the section intended to be filled in by parents/caregivers; we adapted this to an online format. The form comprises a list of actions and motor abilities of different levels of complexity (e.g., from sitting or beginning to stand or walk, to climbing up and down the stairs or completing puzzles) and sub-actions (e.g., sitting unsupported for at least one minute, taking at least two steps, etc.). Caregivers were asked to indicate the frequency with which their child carried out each specific action, choosing a value from Almost always, Often, Sometimes, Rarely and Never. Parents were asked to also mark as 'Almost always' any skills that the child used to exhibit but that they had grown out of. For our analysis, we then assigned the following numerical values: Almost always = 5; Often = 4; Sometimes = 3; Rarely = 2; Never = 1. For the

purposes of this study, we examined the two motor variables associated with independent locomotion: crawling and walking. We adopted conservative criteria to code for these two behaviours. Crawling was intended to mean locomoting across the floor on hands and knees, without the abdomen touching the ground, for at least 5 feet. Similarly, we considered only stable walking behaviour, unsupported and employed by the child as their most common form of locomotion.

Results

Descriptive statistics

Sleep variables

An increase in night-time sleep and a decrease in daytime sleep was observed over the period of data collection (see Figure 1).

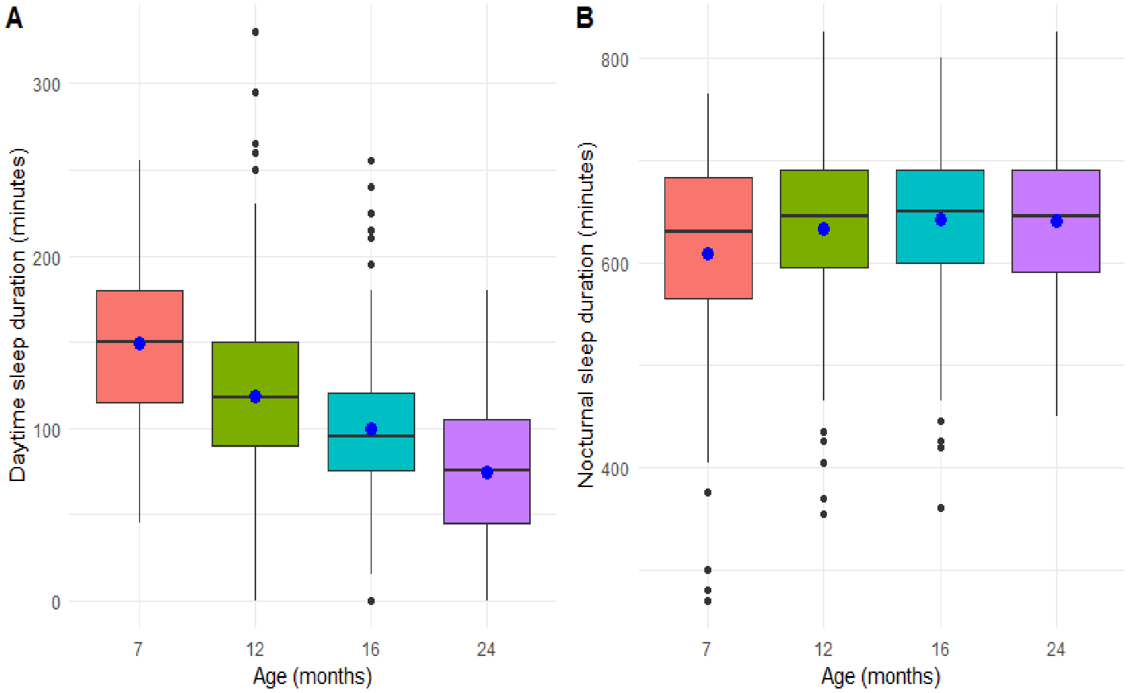

Figure 1. Average and median sleep duration (in minutes) during the day (A) and during the night (B) across age. The average score is indicated with a blue dot.

At 7 months, the average time spent asleep during the day was 155 minutes (~2.5 hours). This decreased to 117 minutes at 12 months (~1.95 hours), to 100 minutes at 16 months (~1.6 hours) and to 75 minutes at 24 months (~1.25 hours). Total time spent asleep during the night increased from 588 minutes at 7 months (~9.8 hours), 643 minutes at 12 months (~10.7 hours) and 648 minutes at 16 months (~10.8 hours). It then decreased to 635 minutes at 24 months of age (~10.6 hours), on average. Two ANOVA were carried out to assess whether night-time and daytime sleep duration were significantly different by age. Age had a significant, robust effect on daytime sleep duration ($F(3) = 76.66$, $\eta^2 = 0.21$, $p < 0.001$). The effect size ($\eta^2 = 0.21$) indicates that approximately 21% of the variability in daytime sleep can be attributed to age. In contrast, the effect of age on night-time sleep was also significant ($F(3) = 5.112$, $p = 0.00165$), but with a smaller effect size ($\eta^2 = 0.017$), indicating a comparatively weaker influence of age on night-time sleep duration. Table 1 in Appendix 1 summarises the number of naps (NN) and night awakenings (NNA) and the proportion of night-time sleep (N/D) per age. The number of naps gradually decreases with age. The number of night awakenings also decreases with age. As the night awakenings that were reported to us are only those that parents are aware of, they are likely to be those signalled by the child with calls or crying. For this reason, NNA may not include all night awakenings, as children may sometimes soothe themselves back to sleep. N/D increases with age, progressively shifting from 0 to 1 across the four data collection points. The figures below (2-4) summarise the patterns of NN, NNA and N/D across age.

Figure 2. Number of naps by age.

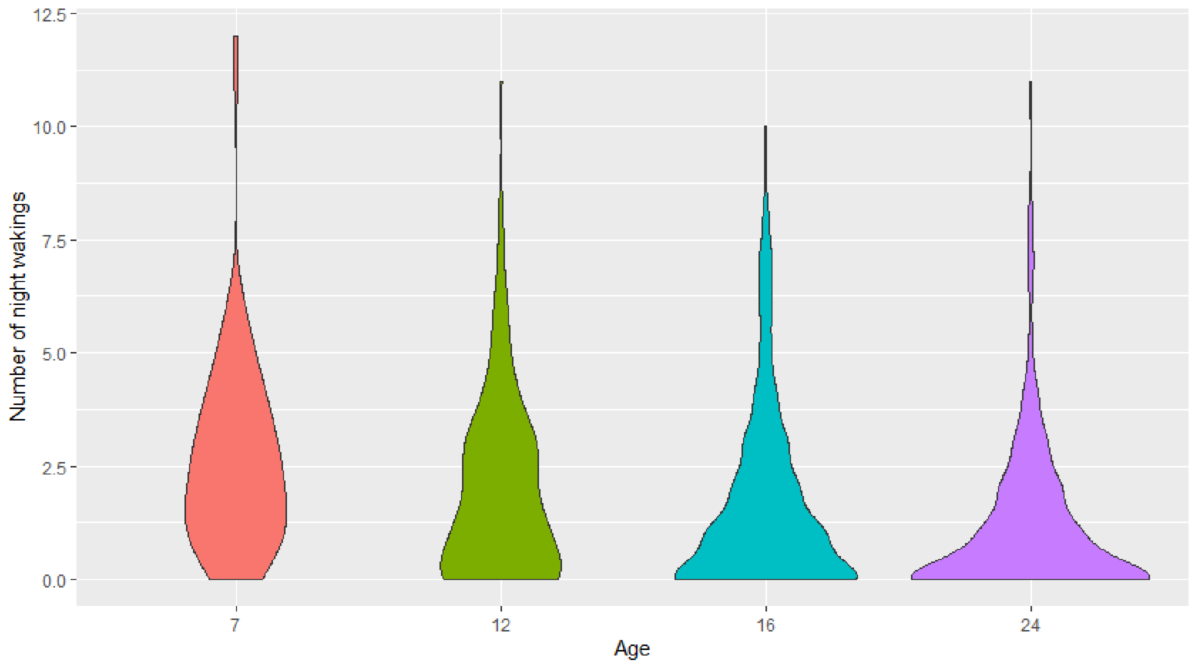

Figure 3. Number of night awakenings by age.

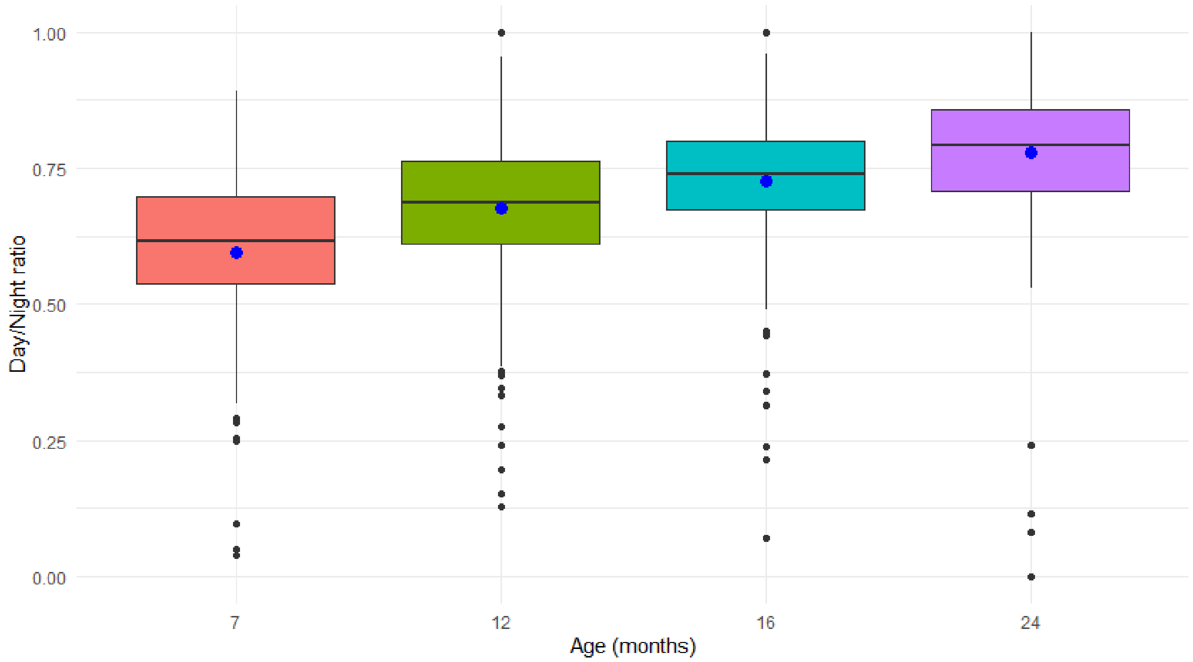

Figure 4. Day/Night sleep ratio by age. Values closer to 1 indicate more sleep occurring at night.

Vocabulary size

Figures 5 and 6 show the growth of receptive and productive vocabulary across age.

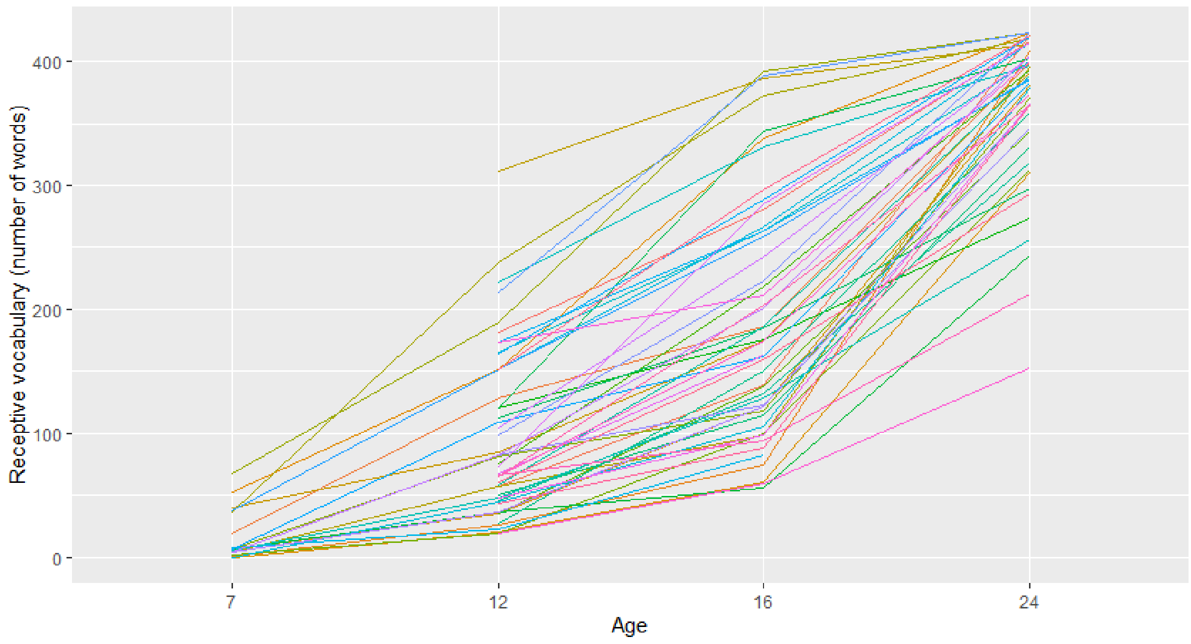

Figure 5. Receptive vocabulary across age.

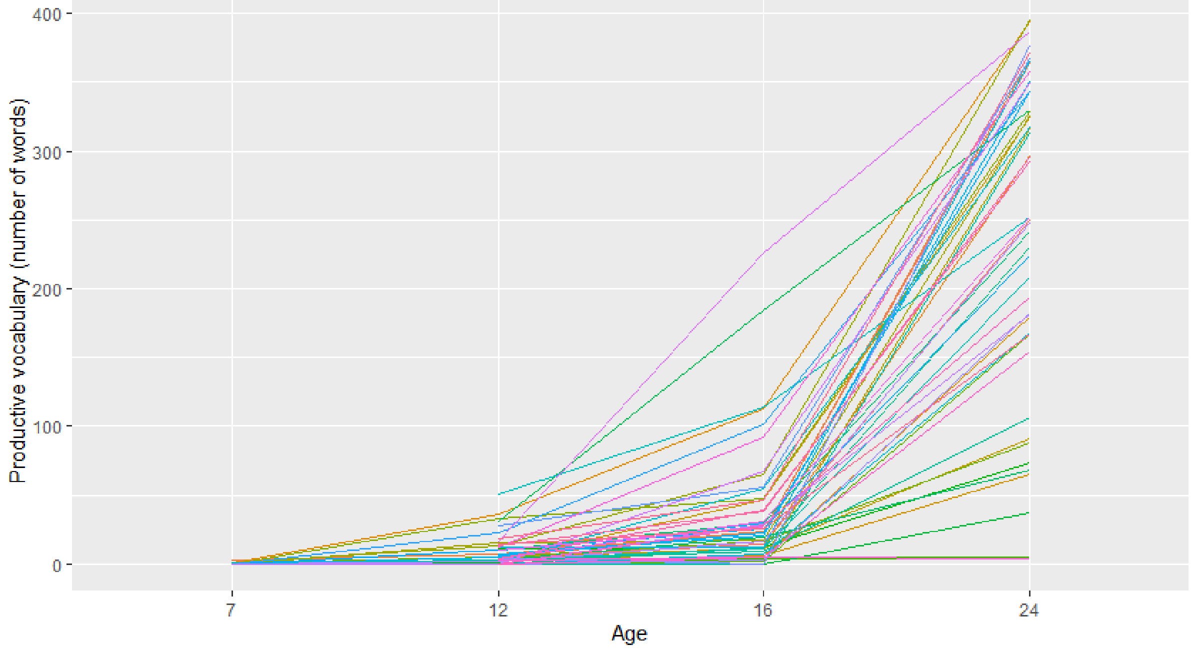

Figure 6. Productive vocabulary across age.

Motoric skills

Figure 7 illustrates the percentage of children categorised by the frequency of crawling at each age, ranging from those who never crawled to those who crawled rarely, sometimes, often, or always.

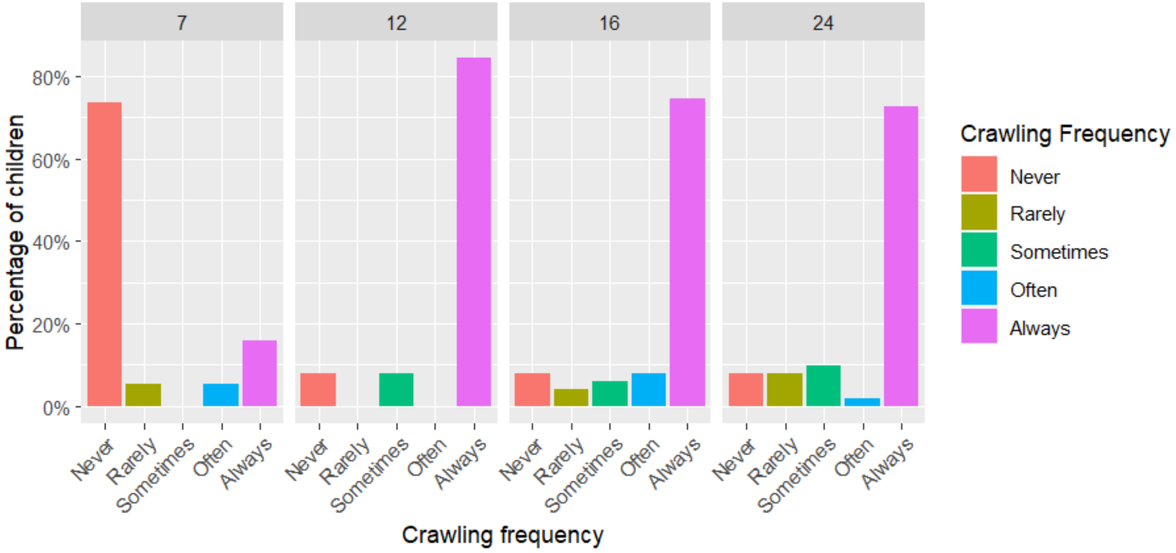

Figure 7. How often children were reported to crawl at each age.

Figure 8 shows the distribution of children based on their walking frequency at each age, ranging from never walking to walking rarely, sometimes, often or always.

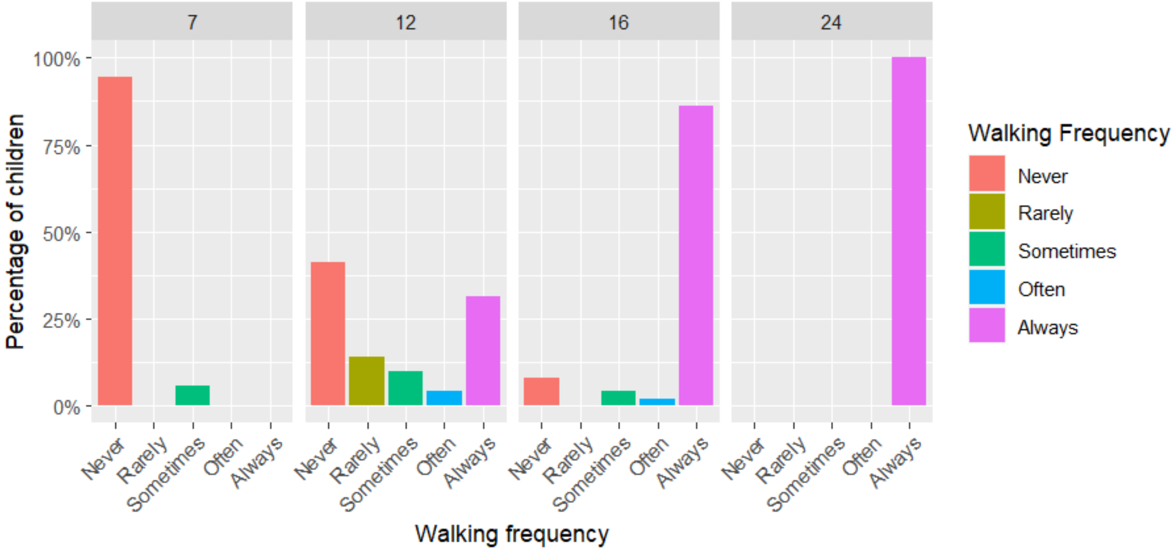

Figure 8. How often children were reported to walk at each age.

Crawling frequency increased sharply at 7 and 12 months, after which it stabilised. Walking frequency had a more gradual increase across age.

Main analysis

We wanted to understand whether the development of sleeping patterns and the motor skills associated with independent locomotion have a combined influence on vocabulary development, whether receptive, productive or both. Accordingly, we ran two mixed effects models with sleep and motoric development as independent variables and vocabulary as the dependent variable.

Correlations between sleep parameters

To improve the interpretability of our mixed effects model, we checked the correlation between the sleep variables before inputting them into the model. The results of these correlations are shown in Table 1.

Age	**Correlation**	**df**	**R**
7	NN ~ NNA	97	0.09
	NN ~ N/D	97	-0.48***
	NNA ~ N/D	97	-0.42***
12	NN ~ NNA	252	-0.06
	NN ~ N/D	252	-0.26***
	NNA ~ N/D	252	0.11
16	NN ~ NNA	252	0.039
	NN ~ N/D	252	-0.23***
	NNA ~ N/D	252	0.03
24	NN ~ NNA	243	-0.027
	NN ~ N/D	243	-0.29***
	NNA ~ N/D	243	-0.11

Table 1. Correlations between number of naps (NN), number of night awakenings (NNA) and the night over daytime sleep ratio (N/D) per age.
Significance codes: *** = ($p \leq 0.001$); ** = ($0.001 \leq p \leq 0.01$); * = ($0.01 \leq p \leq 0.05$).

NN correlated with N/D at all ages, and NNA correlated with N/D at 7 months. Therefore, only N/D was included as a sleep variable in the model. This variable provides information about both daytime and night-time sleep, contrary to NN (daytime sleep only) and NNA (night-time sleep only).

Statistical models

The univariate data analysis identified subsets of data of varying informativeness in terms of variance. Table 2 and Figure 7 suggest that crawling frequency in our sample reached its peak by 12 months and then levelled off. Similarly, Table 3 and Figure 8 show a sharp increase in walking frequency between 12 and 16 months, clearly distinguishing two phases - a pre- and a post-walking onset phase. Thus data about crawling frequency at 12, 16 and 24 months are unlikely to be informative as they contribute little variance; virtually all the children were reported to be crawling at those ages. This applies to data about walking frequency at 7 months, when virtually no infant was reported to be walking. Similarly, the number of words produced at 7 months is virtually zero (Figure 6). Therefore, productive vocabulary at 7 months is likely to be relatively uninformative.

Given the trends described above, we divided the dataset into two subsets: 7-16 months of age, for which we investigated the effects of sleep and crawling frequency on receptive vocabulary, and 12-24 months of age, for which we investigated the effects of sleep and walking frequency on productive vocabulary. Based on this, we built and ran two separate mixed effects models. Their results are compared in the Discussion section.

Statistical analysis was run in R (R Core Team, 2015). We conducted linear mixed effects regression models using the lme4 package (Bates et al., 2015). P-values were calculated via likelihood ratio model comparisons tests using the anova function in R. This method quantified the relative influence of each predictor variable on either productive or receptive vocabulary, depending on the model. In our models, vocabulary constituted the dependent variable, with N/D, motor ability (crawling or walking frequency, depending on the model) and age as fixed effects predictor variables. As the experiment involved repeated measures across multiple participants, the variable *participant* was included in the model as a random effect.

Model 1 - The effect of age, crawling frequency, daytime/night-time sleep ratio on receptive vocabulary between 7 and 16 months

The first model tested the effects of age, crawling frequency and N/D on receptive vocabulary. Any of these predictor variables could affect receptive vocabulary at some ages but not others; to check this we included the interactions of N/D and crawling frequency with age. If the interaction between crawling frequency and/or N/D with age is significant, it will suggest that the interacting predictor affects receptive vocabulary only at specific ages. Table 2 reports the results of the model comparisons testing for significant effects of each predictor variable.

Variables	**Chisq**	**Df**	**p**
N/D	3.8431	1	0.049*
age	529.51	2	< 0.001***
crawling	83.647	1	< 0.001***
N/D*age	10.117	2	0.0063*
crawling*age	37.006	2	< 0.001***

Table 2. Effects of predictor variables on receptive vocabulary size.
Significance codes: *** = ($p \leq 0.001$); ** = ($0.001 \leq p \leq 0.01$); * = ($0.01 \leq p \leq 0.05$).

Age, N/D and crawling each have individual effects on the model. However, interactions of age with both N/D and crawling were significant, suggesting that these two variables were associated with vocabulary at specific ages. Correlations between the two predictor variables and receptive vocabulary at each age were measured to further investigate this finding, The results are shown in Figures 9 and 10.

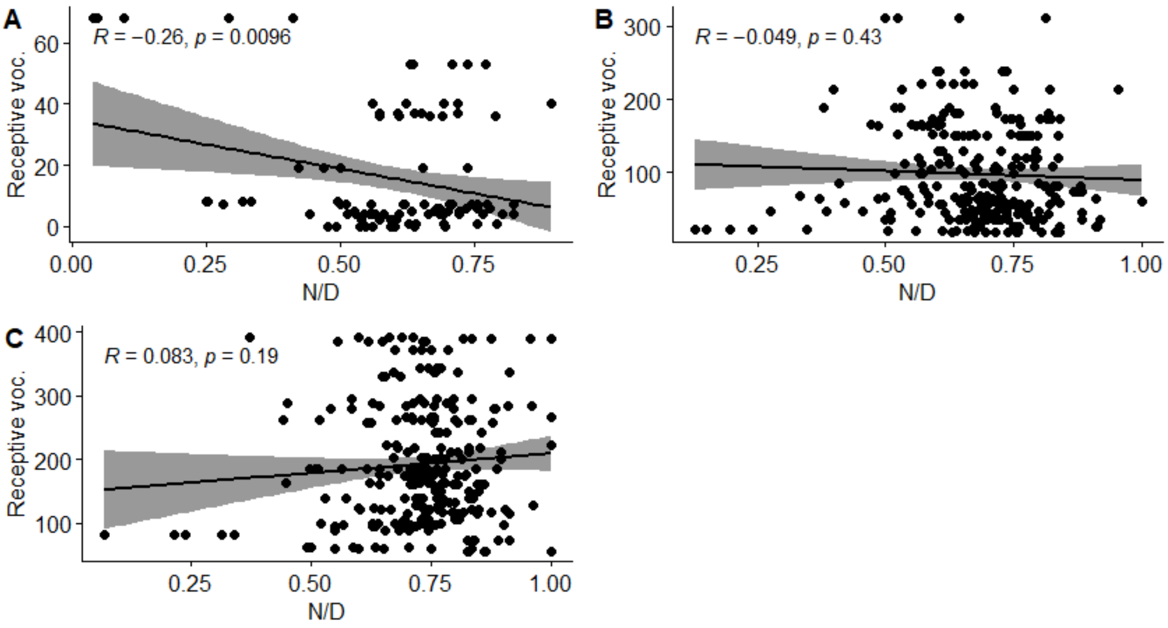

Figure 9. Correlations between N/D and receptive vocabulary at 7 months (A), 12 months (B) and 16 months (C).

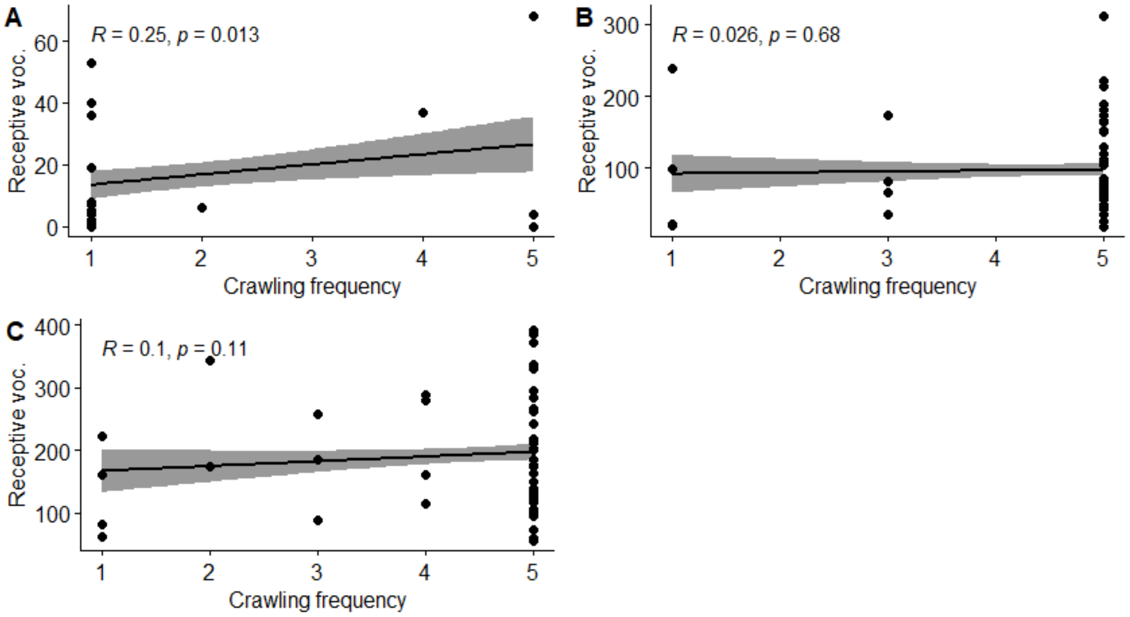

Figure 10. Correlations between crawling frequency and receptive vocabulary at 7 months (A), 12 months (B) and 16 months (C).

The significant correlations were receptive vocabulary and N/D at 7 months (negative) and receptive vocabulary and crawling frequency at 7 months (positive).

Model 2 - The effect of age, walking frequency and daytime/night-time sleep ratio on productive vocabulary between 12 and 24 months

The second model investigated the effects of age, walking frequency, N/D and their interactions with age on productive vocabulary at 12, 16 and 24 months. The results are shown in Table 3.

Variables	**Chisq**	**Df**	**p**
N/D	1.3667	1	0.2424
age	792.34	2	< 0.001***
walking	2.3722	1	0.1235
N/D*age	8.9698	2	0.01128*
walking*age	7.7903	1	0.005253**

Table 3. Effects of predictor variables on productive vocabulary size.
Significance codes: *** = ($p \leq 0.001$); ** = ($0.001 \leq p \leq 0.01$); * = ($0.01 \leq p \leq 0.05$).

The only significant individual predictor was age. However, interactions of age with both N/D and walking were significant, suggesting that these two variables are differently associated with productive vocabulary at specific ages. Correlations between the two predictor variables and productive vocabulary at each age were measured and their results are represented in Figure 11 and 12.

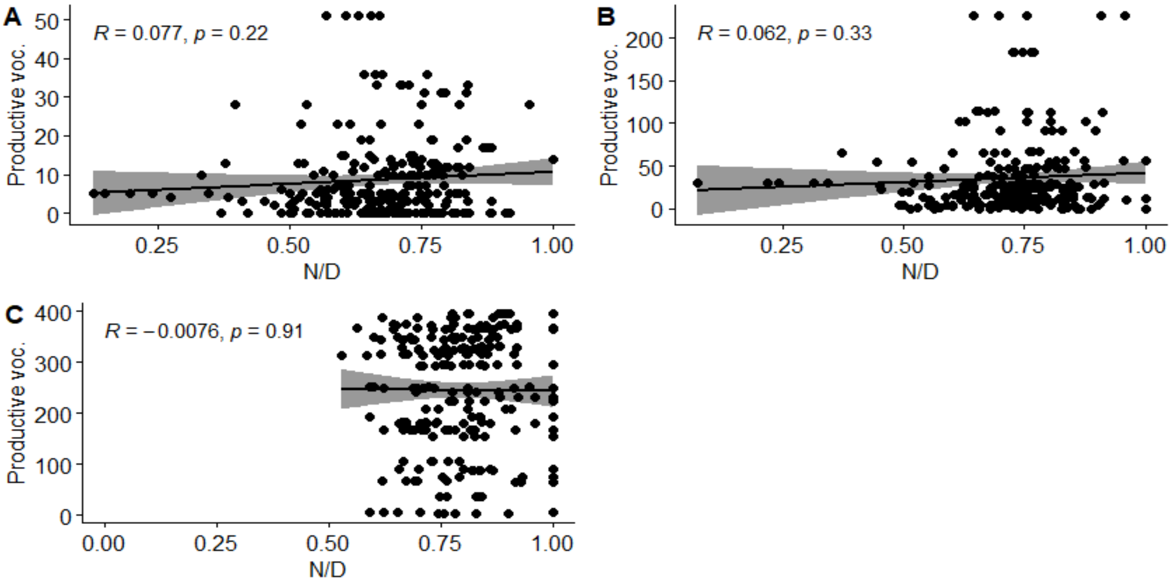

Figure 11. Correlations between N/D and productive vocabulary at 12 months (A), 16 months (B) and 24 months (C).

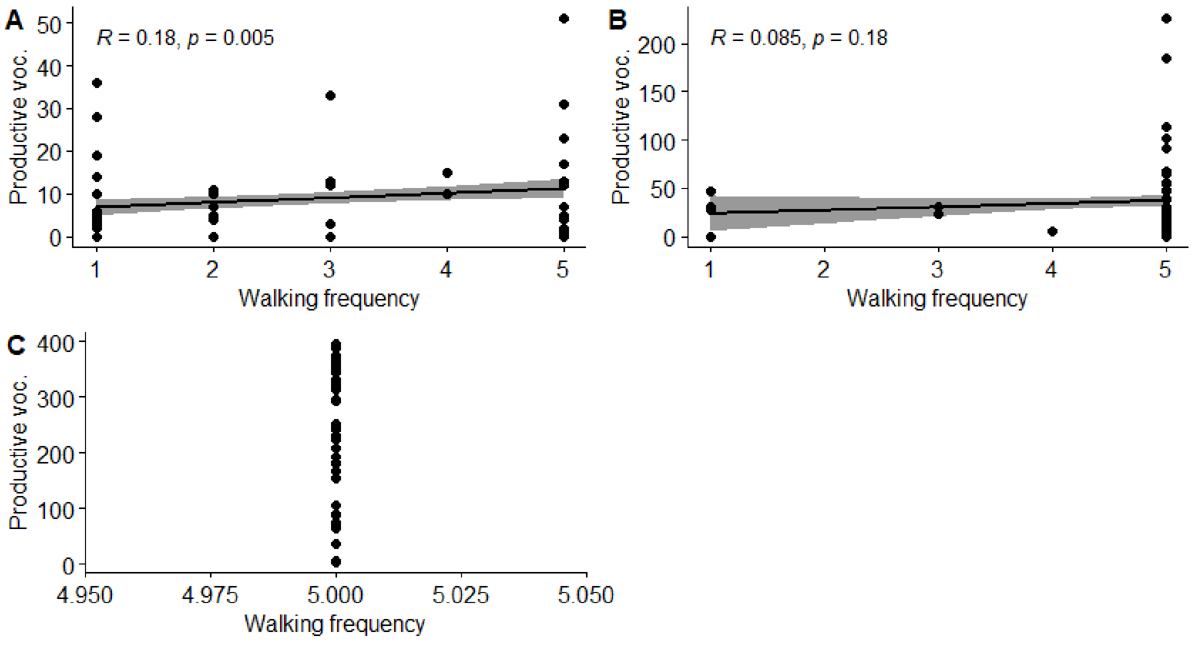

Figure 12. Associations between walking frequency and productive vocabulary at 12 months (A), 16 months (B) and 24 months (C).

The only significant relationship was between productive vocabulary and walking frequency at 12 months (positive).

Exploratory analysis: Average motoric development and sleep parameters

The proportion of nighttime vs. daytime sleep correlated significantly with vocabulary only at 7 months. At this age, it was negatively associated with receptive vocabulary. This finding indicates that, at 7 months, infants who sleep *longer during the day* also have *larger* receptive vocabularies than infants who sleep comparatively longer at night. A possible explanation for this result is that at this age infants might still rely heavily on daytime sleep for the consolidation of novel words due to their less mature memory systems. In this scenario, infants who sleep less during the day might have fewer chances to consolidate their vocabulary knowledge.

The following exploratory analysis investigates the possibility that the associations between N/D and smaller receptive vocabulary at 7 months might reflect wider associations between N/D and general development. We did not collect a comprehensive measure of overall development. Accordingly, a general motor score based on the responses to the Vineland Adaptive Behavior Scales (Motor Skill

Domain) (*av.mot*) was calculated and was used as a proxy for general level of (motor) development. Table 4 and Figure 13 show the outcomes of this analysis.

Age	**Correlation**	**t**	**df**	**R**
7	**N/D ~ av.mot**	**-2.7112**	**97**	**-0.27****
12	**N/D ~ av.mot**	**2.7913**	**252**	**0.17****
16	**N/D ~ av.mot**	**3.8705**	**252**	**0.24*****
24	N/D ~ av.mot	1.7472	243	0.11

Table 4. Correlations between average motor skill score and N/D across age.
Significance codes: *** = (p ≤ 0.001); ** = (0.001 ≤ p ≤ 0.01); * = (0.01 ≤ p ≤ 0.05).

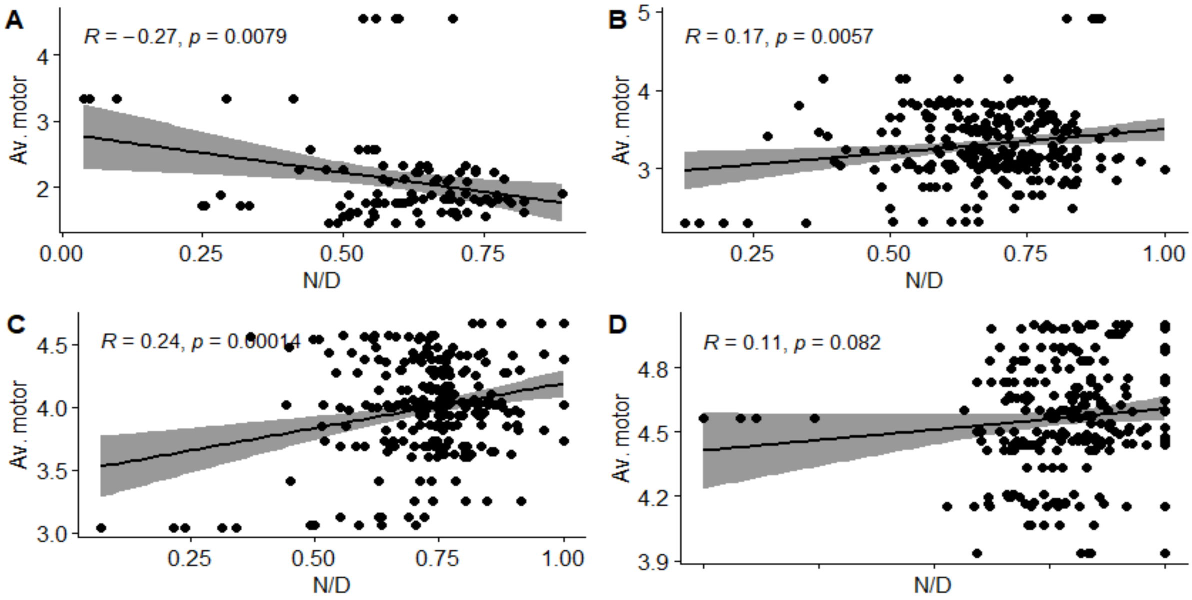

Figure 13. Correlation between daytime/nighttime ratio and average motor score at 7 months (A), 12 months (B), 16 months (C) and 24 months (D).

What is evident from Figure 13 is that the observed trend of the association between av.mot and N/D changes dramatically after the first birthday. The inverse relationship between these two variables at 7 months (modest but significant) mirrors the same direction and magnitude of the correlation between N/D and receptive vocabulary at this age. However, this relationship is reversed at 12 and 16 months of age. At later ages, infants who slept longer at night than in the daytime had significantly higher motor scores than those who slept longer during the day, although with small effect sizes. By 24 months N/D was no longer associated with overall motor score.

Discussion

The first two years of life are characterised by dramatic changes in infants' knowledge about the world and themselves (Thelen & Smith, 1994; Vihman, 2014). Among these changes the emergence of the first lexical networks, the onset of self-locomotion and the evolution of sleep patterns towards more consolidated overnight sleep stand out in particular. Prior studies have noted some developmental relationship between sleep regulation, self-locomotion and vocabulary growth. Nevertheless, their interconnectedness has not previously been investigated. The present study was designed to address this gap and provide a biologically grounded account of vocabulary development in the first two years of life. Our approach is holistic and embodied; It studies vocabulary growth as a process intimately related to the growth of memory networks and, at the same time, as a product of the on-going interaction between the developing body and the environment.

In this study age alone proved to be a significant predictor of vocabulary in each of the models, but in each of the models it also interacted in significant ways with one or both of the main predictor(s) (i.e., the sleep and motor variables). This suggests that the relationship between self-locomotion, sleep maturation and vocabulary changes with age. Accordingly, we ran a series of correlation analyses to examine the relationship between vocabulary and the sleep and motoric variables at each age.

A larger proportion of sleep at night was associated with smaller receptive vocabularies at 7 months. No associations between vocabulary and the proportion of night over daytime sleep were observed at any other age. This finding was unanticipated, given the emphasis in the literature on the developmental importance of the shift towards more established night-time sleep (e.g., Gibson et al., 2011; Bernier et al., 2010; 2013; Dionne et al., 2011; Knowland et al., 2021). The findings of the exploratory analysis suggest a tentative explanation. This analysis showed that 7-month-olds who slept proportionately more at night also had lower motoric scores. This reflects the main analysis finding associations between the proportion of nocturnal sleep and receptive vocabulary. However, when infants reached 12 and 16 months, this pattern reversed; children who slept proportionately longer at night had higher motor scores. At 24 months, this correlation was no longer significant. These results suggest that the relative importance of daytime and night-time sleep changes over early childhood (see Thorpe et al., 2015). In early infancy more sleep may be needed throughout the day to propel the consolidation of motor skills as well as of vocabulary, as infants' memory systems are less mature (Esterline & Gómez, 2021; Gómez & Edgin, 2015). So infants who nap less and sleep proportionately more at night could be missing opportunities to consolidate their skills. In later infancy, children accumulate sleep pressure (i.e., the need to sleep) more slowly; this allows them to remain awake for longer periods of time (Esterline & Gómez, 2021; Kurth et al., 2016). Thus, they transition from napping to more nocturnal sleep. At this point, infants who sleep more at night may benefit more from complete and interleaved sleep cycles than infants who sleep less during the night (see Werchan et al., 2021). In other words, nocturnal sleep becomes progressively more important to consolidation and development as napping decreases. At age two, when some children start to settle into monophasic sleep, these associations are no longer as strong.

Associations between self-locomotion and vocabulary were also found at 7 months. Infants who crawled more often at this age had significantly larger receptive vocabularies. This mirrors the findings at 12 months, when walking and productive vocabulary are the variables of interest. At this age children reported to be walking more frequently also had larger productive vocabularies. No associations were found between self-locomotion and vocabulary at 16 or 24 months. Crawling behaviour typically emerges between 7 and 10 months. Independent walking is commonly observed by around 14 months, on average. We measured crawling and walking behaviour in a conservative way, considering only crawling on hands and knees and unsupported walking. So, crawlers and walkers in our 7- and 12-month age groups, respectively, are particularly advanced in self-locomotion. Together with our findings, this indicates that the associations between motoric skill and vocabulary are more evident in the period when self-locomotion skills are just beginning to emerge, and that such associations grow progressively weaker as the skill becomes more established.

This is consistent with the idea that the emergence of new motor skills, and self-locomotion skills specifically, opens the way to new patterns of exploration of and interaction with the world, and to new ways in which the world interacts with the child, with important consequences for vocabulary development. So the 7-month-olds in our sample who were reported to be crawling more frequently probably experienced increased social interactions with their caregivers, as reported in the literature (Campos et al., 2000). In turn, richer social interactions and distal referencing increase the number of words infants are exposed to; this would then contribute to making the receptive vocabularies of 7-month-old crawlers larger than those of their non-crawling peers. The relationship between walking frequency and productive vocabulary observed at 12 months can be similarly interpreted. Children walking independently interact with caregivers for longer periods and vocalise more (Clearfield, 2011); more vocal practice and more frequent interactions facilitate productive vocabulary development (Clearfield, 2011). These findings are both consistent and inconsistent with Walle and Campos (2014), where the level of linguistic input from the parent was associated with receptive and productive vocabulary in walking but not in crawling infants, independently of age. Alternatively, it could be argued that the positive associations between self-locomotion and vocabulary size observed at these ages might be more directly due to the infants' overall developmental status. In this interpretation, the correlations are evident because infants who confidently crawl or walk at 7 and 12 months are also particularly advanced motorically; their vocabulary might be higher than their non-crawling or non-walking peers because of their more advanced general development, rather than as a result of enhanced social interactions. To develop a fuller picture of the association between the onset of self-locomotion and vocabulary growth future longitudinal studies could add observations of parent-child interactions, and child vocal behaviour, before the emergence of the self-locomotion skill, after its appearance and after the child has mastered the skill. Concurrently, motor advancement should be recorded with the same frequency. It should then be tested whether the emergence of the skill is accompanied by markedly richer interactions and vocalisations and an increase in vocabulary. If the increased interactions and/or vocalisations have a stronger effect on vocabulary growth than motoric development rate alone, that would suggest that the associations between motor skill and vocabulary development at the age of emergence of the skill are related to increased language directed to and produced by the child, rather than to general motor skill level.

Twelve months was not only the age at which associations between walking behaviour and vocabulary emerged. Interestingly, 12 months also corresponded to an evident turn in the developmental patterns of the sleep, motoric and vocabulary variables. The interval between 12 and 16 months clearly marked the passage from two naps and two night awakenings to one of each, on average (see Figures 2 and 3). Similarly, walking behaviour strongly increased after 12 months, as did productive vocabulary across our sample (see Figures 6 and 8).

Thus, our study shows that significant interconnections exist between self-locomotion, vocabulary and sleep patterns and that these emerge at ages of marked developmental change. In the motor domain, 7 and 12 months are ages at which crawling and walking start to become established (Størvold et al., 2013; Bayley, 1969 and Frankenburg, et al., 1992, as reported in Adolph & Robinson, 2015). In the linguistic domain, 7 and 12 months are approximately the ages at which speech comprehension and babbling behaviour are observed and first words are produced, respectively (Bergelson & Swingley, 2012; Oller, 2000; Schneider et al., 2015). Between 8 and 12 months, infants consolidate their ability to initiate and self-regulate sleep independently, which is essential for sustaining nocturnal sleep (Paavona et al., 2020; Henderson et al., 2011). In a dynamic systems framework, the following model could be theorised to link these domains, based on the idea that development is self-regulated and emerges through the interaction of multiple systems with one another and with the environment (Thelen & Smith, 1994). As infants begin to crawl, the increased social interactions change the amount and kind of speech that is directed to the infant; babble mediates infants’ attention to the words they hear (DePaolis et al., 2011; Majorano et al., 2014), with potential effects on which of those words are retained in memory. Concurrently, infants' self-regulatory abilities develop and gradually enable babies to sustain longer periods of sleep. This, together with the development of the brain and memory systems through sleep development (Lokhandwala & Spencer, 2022) and babble practice (Keren-Portnoy et al., 2010), supports the consolidation and reorganisation of their growing lexical networks and motor abilities. At the same time, infants’ ongoing gross and fine motor development opens new ways to explore the environment as well as to vocalise. This practice supports the retention of more words, which provides the basis for first word production (Vihman, 2022). This scenario is hypothetical and the direction of the relationships between self-regulation, motoric skill and vocabulary is not fully understood. Nevertheless, this study has provided strong evidence for the interconnectedness of these domains and makes a case, building on the existing literature, for pursuing the study of development as a dynamic process where self-regulatory mechanisms, sleep regulation, social interactions, motor and vocal development co-participate in the process of vocabulary growth.

Previous research has also found associations between sleep patterns and motoric skills. As infants begin to crawl or walk they go through a temporary period of increased nocturnal sleep disturbance (Scher & Cohen, 2005; Scher, 2005; Berger & Moore, 2021). Although it may seem counterintuitive, recent evidence suggests that these disturbances are associated with the consolidation of the motoric skill (Scher, 2005; DeMasi et al., 2021). Increased motor activity during nocturnal sleep when a new motor skill is being acquired has been linked to twitches (Blumberg, 2010; 2015). Twitches during infant sleep have been theorised to drive sensorimotor integration and the consolidation and reorganisation of neural patterns in the motor regions of the brain (see Sokoloff et al., 2021; Del Rio-Bermundez & Blumberg, 2021). The temporary disruption of sleep might then be due to the occurrence of twitches, as the increased motor activity and arousal could disrupt sleep (Berger & Moore, 2021). We did not examine the relationship between sleep maturation and the development of self-locomotion skills, as the interpretation of these relationships would go beyond our areas of expertise. However, these recent findings point towards interesting directions for future research.

Our data collection points were relatively widely separated. Future large-scale studies would do well to employ a finer-grained data collection schedule to better understand how the relationship between sleep, self-locomotion and vocabulary unfolds over time. Also, future studies would do well to corroborate parental reports with actigraphy measures. Our results corroborate the trends observed in much of the previous literature on sleep patterns. For example, the proportion of night-time sleep was found to increase and that of daytime sleep to decrease significantly with age. However, the developmental decrease in daytime sleep was sharper than the increase in night-time sleep. These results corroborate the trends observed in previous studies (e.g., Galland et al., 2012), and suggest that variation in the value of the proportion of daytime and night-time sleep (N/D) might be more closely related to variations in daytime than in nocturnal sleep. The findings also accord with the existing literature on sleep patterns in infancy, with a decrease observed in both numbers of naps (NN) and of night awakenings (NNA) with increasing age (Iglowsetin et al., 2003). Parental reports of infant sleep are relatively accurate (e.g., Scher et al., 1992; Kaplan et al., 2012). However, parent-reported night awakenings might not reflect the actual number of times the child awoke during the night, because many children (especially older ones) may self-soothe after waking (Anders et al., 1979). Although we excluded number of night awakenings from our final model, and the changes in and duration of night-time sleep agree with the existing literature, our measures of night-time sleep may not be fully accurate.

There is no consensus as to when to consider that a motor skill has emerged (Berger & Moore, 2021); accordingly, cross-study comparisons must be made with caution. Furthermore, it is important to note that, although motor milestones seem to propel linguistic development in typically developing children, alternative paths to the acquisition of language are also possible, as evidenced by the fact that children unable to walk do generally develop language. These children may gain relevant input from their environment (supporting their linguistic development) through means other than self-produced locomotion. Reaching motor milestones is thus neither sufficient nor necessary for language acquisition (Iverson, 2010). It is also evident that children demonstrate some linguistic abilities before they can sit or walk. Future studies on the associations between motor skill and vocabulary development in these populations are therefore needed.

Conclusions

This study has shown that sleep regulation and self-locomotion are associated with vocabulary measures at specific ages. Our findings suggest that these associations emerge at ages of marked developmental change. Crawling frequency and receptive vocabulary were positively associated at 7 months. At this age, a smaller proportion of sleep during the night was associated with poorer general motor skill and smaller vocabularies. However, these associations changed after 12 months of age, suggesting that the relative importance of daytime and night-time sleep shifts with age. The first birthday also marked dramatic changes in sleep patterns; 12 months was also the age at which walking frequency was positively associated with productive vocabulary. Crucially, 7 and 12 months are ages at which first stable crawling and walking behaviour start to emerge, respectively, and also ages at which important changes in language and self-regulatory abilities can be observed.

Although these results are mainly correlational, they strongly suggest that self-locomotion, vocabulary and sleep patterns are mutually intertwined. Specifically, these associations are stronger at ages at which the most marked developmental changes occur. Important questions for future research emerge from our findings. For example, is letting go of naps and, in general, the transition to longer and more uninterrupted night-time sleep mainly age-related? To what extent is it a product of exogenous factors, e.g., family routines and cultural practices, as compared with endogenous factors, i.e., memory system maturation and changes occurring in other areas of development? Does sleep regulation trigger developmental cascades in language development, and if so, why? And ultimately, what else can we learn about the associations between sleep, motor and language development that we have identified? Our findings indicate that these questions can be answered by conceptualising development as a holistic process involving self-regulation and memory mechanisms as well as motoric and linguistic abilities.

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Appendix

Appendix 1: Number of Naps (NN), Number of Night awakenings (NNA) and (N/D) by age.

Age	Sleep parameter	min	max	mean
7	NN	1	5	2.647059
	NNA	0	12	2.488095
	N/D	0.03846154	0.8909091	0.5876422
12	NN	0	3	1.703349
	NNA	0	11	2.076555
	N/D	0.1276596	1	0.6790389
16	NN	0	2	1.213115
	NNA	0	10	1.545082
	N/D	0.07096774	1	0.7230579
24	NN	0	3	0.9291667
	NNA	0	11	1.05
	N/D	0	1	0.7804367

Note: NN and NNA are whole numbers. N/D is a proportion and the values are included between 0 and 1. The closer these are to 1, the bigger the proportion of sleep happening at night relative to during the day.

General discussion and conclusion

Sleep is the most prevalent behaviour in infants; infancy is also a period of marked developmental change, over multiple dimensions. In particular, the first two years of life are characterised by the emergence and fast-evolving development of the first phonological and lexical networks, as well as the onset of self-locomotion. The three studies in this PhD thesis were conducted to investigate these developmental domains as interrelated phenomena, with the aim of providing a biologically sound account of word learning. This concluding chapter recapitulates the findings of the preceding articles, discusses their broader implications and significance and outlines avenues for future work.

Summary of key findings

The systematic review article surveyed existing research on the connections between sleep and word learning in children under three years of age. This was done to summarise current knowledge about this topic, identify any gaps and inform future work, including the two original research studies in this thesis. Only 16 papers were found to address the topic directly. Overall, the review indicated that word learning in infancy is supported by memory mechanisms similar to those underlying nonlinguistic memory consolidation. Sleep shortly after exposure to new linguistic information was found to maintain, or even enhance, memory for that information. Children who napped shortly after being introduced to new words showed better memory for those words compared to children who did not nap. Additionally, sleep was linked to flexible use of lexical and phonological knowledge, including generalising word meanings and extracting words from running speech. This review also found that sleep has longitudinal effects on word learning, with sleep patterns in early infancy (e.g., number of daytime naps, proportion of time spent asleep at night compared to during the day) predicting vocabulary growth and vocabulary knowledge at school entry. In some studies, existing lexical knowledge was found to mediate the effects of sleep on word learning. For example, vocabulary size predicted the magnitude of post-sleep memory benefits.

The experimental study was designed to address one of the gaps identified in the systematic review article, namely, the effects of sleep on word form generalisation. The systematic review established that the generalisation of new linguistic information relies on the same mechanisms that support generalisation of nonlinguistic memories, and reported consistent evidence supporting the role of sleep in the generalisation of word meanings. Similar to the way that the generalisation of word meanings entails recognising visual regularities among referents of the same category, and the subsequent extension of the category label to new related objects, word form generalisation relies on extracting phonological regularities across different auditory instances of the same word and forming an abstract phonological representation of the word form. However, no studies had investigated whether sleep has similar effects on word form generalisation, despite its known associations with other kinds of memory generalisation. Therefore, this study aimed to determine if a nap immediately following auditory presentation of words uttered by one talker would enhance infants' recognition of the same word forms produced by a different talker. This study also investigated whether this advantage persisted the following day, considering previous research on generalisation performance following sleep in infants. The results indicated that infants who napped shortly after word exposure improved their word form generalisation 24 hours later. On the other hand, infants who did not nap within two hours following exposure to the words showed no significant improvement across testing sessions.

The questionnaire-based study originated as a response to the mixed findings noted within the longitudinal studies discussed in the systematic review. These studies examined the long-term effects of sleep patterns on vocabulary growth in infants of various ages. Two studies (Dionne et al., 2011; Knowland et al., 2022) together show that longer and more stable nocturnal sleep relative to daytime sleep at earlier ages predicts larger vocabularies in subsequent years, and even at school entry. In contrast, negative associations between nocturnal sleep duration and vocabulary growth were found in Horváth and Plunkett (2016), alongside a positive correlation between the number of daytime naps and later vocabulary. Therefore, this study was designed to clarify how sleep regulation, i.e., the progression to more consistent nocturnal sleep and the decrease of naps, influences vocabulary development during the first two years of life, the period marked by significant shifts in sleep regulation. Secondly, this study aimed to evaluate the impact of advances in self-locomotion on vocabulary learning. This objective was driven by significant findings linking the emergence of self-locomotion with vocabulary development, and by the evidence associating the emergence of self-locomotion and sleep perturbations. These interconnected pieces of evidence point to the existence of relationships between language development, motoric skill and sleep patterns. Yet, no studies had examined the relationships between these domains and how they might change over time. Filling this gap was the primary objective of this study. To this end, the study monitored sleep patterns, vocabulary size, and motor skill attainment in a single group of children at 7, 12, 16, and 24 months of age. The results revealed that the proportion of night-time sleep relative to daytime sleep, alongside the attainment of self-locomotion, were linked to vocabulary growth at points of marked developmental change.

Contributions of this thesis

The findings from the systematic review suggest that the consolidation and reorganisation of lexical knowledge follow routes similar to those observed in the consolidation and reorganisation of nonlinguistic knowledge. This conclusion is supported by consistent evidence on the positive effects of a post-encoding nap, sometimes on its own and at other times in combination with nocturnal sleep, on the consolidation and generalisation of novel word-meaning pairs. The associations between electrophysiological activity in the post-encoding nap and subsequent memory performance also suggest a direct role of sleep in language learning. Thus, this review contributes significantly to our understanding of how the first lexical networks are built during infancy and early childhood, making a strong case for the significant involvement of sleep in this process. Additionally, this review provides compelling evidence for the role of existing knowledge in further word learning in early childhood. This topic remains understudied, yet its significance for clarifying the formation of the first networks of phono-lexical knowledge cannot be overstated. Prior research on adults found that the integration of new knowledge into the neocortex is prior-knowledge-dependent; new information that is more consistent with existing knowledge is likely to be consolidated more rapidly (McClelland, 2013).

The review extended these findings to infants: Small but significant evidence was found to suggest that consistency of the to-be-learned information with existing knowledge improves strength at encoding (e.g., Williams & Horst, 2014). In turn, the strength of the memory traces at encoding modulates post-sleep effects on memory as well as the strength of the learning-related electrophysiological activity in post-encoding sleep (Friedrich et al., 2019). This suggests interesting avenues for future research (see “Avenues for future research”, below).

In creating linguistic representations for novel words and therefore building their lexicon, infants face the daunting task of overcoming the acoustic variability in natural speech. Every time a word is uttered by a speaker it will sound different, for many reasons, such as the sentential context, the speaker’s emotional state or their distance from the listener. These differences are even more dramatic when the word is uttered by different speakers, because each speaker has unique vocal tract characteristics. The results from the experimental study in this thesis shed light on a crucial issue in word learning: how do infants recognise different word realisations as 'the same word', despite the unsystematic within- and between-speaker variability?

Research suggests that this ability is still fragile in young infants. At 7.5 months, infants do not seem to be able to systematically recognise words previously presented in isolation in one voice when embedded into passages read in another voice (Houston & Jusczyk, 2000; 2003). Furthermore, at that age infants cannot systematically recognise words (in the same voice) when presented in a different affective state compared to first exposure (Singh et al., 2004). However, at 10.5 months, infants’ ability to recognise words across different voices and affective states is significantly improved (Houston & Jusczyk, 2000, 2003; Singh et al., 2004). Singh (2008) discussed several factors that could contribute to the changes observed between ages 7.5 and 10.5 months. First, this age range coincides with the period during which infants refine phonetic categories and attune them to their native language (Werker & Tees, 1983, 1984). This process of gradual refinement develops infants’ phonetic encoding system and consequently improves their ability to identify recurrent phonological patterns in spoken language. This ability, in turn, aids in the recognition of word forms. Singh (2008) also suggests that the emergence of stable word form generalisation is supported by increasing experience with speech. With age, children hear more speech, which exposes them to words in an increasingly wide range of acoustic forms. This increasing experience with variability in spoken language helps children establish the consistency in the auditory patterns associated with specific word forms. Recognition of these invariant patterns lays the foundation for phonological representations of those words, which serve as the basis for word form generalisation. So continuous experience with speech incrementally updates early word form representations, increasing their generalisability and providing a stronger base for recognising these word forms in different contexts within natural speech (see also Munson et al, 2012). This explanation aligns with usage-based models of phonological development (Bybee, 1999, Pierrehumbert, 2003). According to these models, phonological knowledge emerges from direct use and experience of speech. The redundancy and variability of linguistic input enables the generalisation across recurrent auditory properties that leads to the emergence of categories (also called ‘exemplar networks’, or ‘schemas’) based on shared properties (Bybee, 1999, Pierrehumbert, 2003). Drawing on the role of sleep in facilitating memory generalisation, the experimental study in this thesis investigated whether sleep is associated with the generalisation of the phonological schemas of newly learned word forms. The findings support this hypothesis.

So the contribution of the experimental study is twofold. First, it corroborates the findings from the systematic review and extends them to a previously unexplored aspect of word learning, i.e., phonological learning, in the form of word form generalisation. In fact, this study provides the first evidence that the combination of a timely post-encoding nap with nocturnal sleep is linked to word form generalisation in infancy, at an age where this ability is still developing. This further reinforces the idea that language learning draws on the same memory mechanisms involved in other kinds of learning. Accordingly, as for other forms of memory generalisation (e.g., Werchan et al., 2021), word form generalisation was significantly better after a night's sleep, but only when a nap followed soon after first exposure to the words. Second, the findings of this study indicate that sleep may be involved in the emergence of phonological representations, a finding that is crucial for understanding lexical development (Munson et al., 2012). Thus, the findings of the experimental study not only align with, but bring a fresh insight to usage-based models of the acquisition of phonological knowledge, suggesting an influential role of sleep in this process.

Usage-based phonology is consistent with an embodied understanding of language and cognitive development: Infants learn language by using it, and they use it in conjunction with the interactions of their evolving bodies with the world around them. The questionnaire-based study applied this holistic and embodied conceptualisation of language development to study vocabulary growth longitudinally, in association with the development of sleep regulation and self-locomotion, both of which were previously observed to be associated with vocabulary development. This study is the first to systematically investigate the interrelationships between vocabulary, self-locomotion development and sleep regulation. The findings of this study make several contributions to current understanding of vocabulary growth. First, the transition away from daytime napping and the subsequent consolidation of nocturnal sleep was significantly associated with vocabulary growth and self-initiated locomotion. Second, the associations between these three (apparently independent) domains are not linear, but rather have been found to change over the first two years of life, especially around the first birthday. Third, these associations emerged at ages of particularly sharp developmental change, i.e., 7 and 12 months (Bayley, 1969; Bergelson & Swingley, 2012; Henderson et al., 2011; Oller, 2000; Paavonen et al., 2020; Schneider et al., 2015; Størvold et al., 2013; Tincoff & Jusczyk, 1999, 2012). These changes concern self-regulation, self-initiated locomotion and communication, namely: a) a decrease of daytime naps and night awakenings, demonstrating advances in infants’ ability to self-regulate sleep at night and manage sleep pressure; b) the onset and improvement of self-locomotion (i.e., crawling and walking); c) the first signs of speech comprehension, word form generalisation and babbling at around 7 months and first word production at around 12 months.

Rather than indicating that language development follows an internal schedule of maturational changes happening at prescribed ages, the correlations observed in the questionnaire-based study suggest that vocabulary grows within the spontaneous, continuous and dynamic interactions between the environment and the motor and self-regulatory systems. So these findings complement existing literature in making a case for pursuing the study of vocabulary growth as a dynamic process where self-regulatory mechanisms, social interactions, motor and vocal development are involved.

The overarching research question guiding this PhD thesis aimed to determine whether a discernible link exists between the prevalence of sleep and the developmental progress in word learning witnessed during infancy. The three studies included in this thesis yielded results in support of such a link. Nevertheless, uncharted research areas remain that could further enrich our understanding of this link, as detailed in the next section.

Avenues for future research

Each of the articles in this thesis suggests several lines of research for future studies. Two recurrent themes are identified and discussed here.

Role of existing knowledge

Current research suggests that existing knowledge can mediate the effects of sleep on memory consolidation (Drosopoulos et al., 2007; McClelland, 2013). For example, larger productive vocabularies are associated with better post-sleep recall and integration of novel words in children (e.g., Henderson et al., 2015; Horváth et al., 2015). Furthermore, novel words that are phonologically similar to known words are recalled better than dissimilar words and sleep-associated memory benefits are stronger for words without phonological neighbours and stronger in children than in adults, i.e., in overall smaller networks (James et al., 2019). These findings collectively suggest that current lexical and phonological knowledge should be considered when examining the consolidation and integration of new linguistic knowledge and the role of sleep in this process. However, no prior research investigated how existing knowledge influences word learning in the preverbal period, when phono-lexical networks are relatively small.

Infants' babble, a typical early form of vocal practice that entails the production of adult-like syllables, is closely related to language development (Vihman, 2022). For example, the stable emergence of two supraglottal consonants in infants’ vocal behaviour predicts first word production (McGillion et al., 2017). Performance in phonological memory tasks is influenced by the specific sounds that young toddlers are able to produce (Keren-Portnoy et al., 2010). Additionally, first words tend to contain sounds similar to those that the child has used or is using in babble (Vihman et al., 1985; McCune & Vihman, 2001), indicating the importance of babble as practice for meaningful speech. Babble also influences speech processing by imposing an articulatory filter (Vihman, 1993, 1996; Vihman et al., 2014) on the individual child's experience of heard speech. This is evidenced in the fact that infants' attention to speech is affected by the specific sounds that they can produce; attention is differentially both attracted to sounds that resemble those in the child's repertoire and, at a more advanced stage, to sounds that fall outside the child's repertoire (DePaolis et al., 2011; Majorano et al., 2014). This literature suggests that babble constitutes an early form of knowledge that clearly affects language and, as such, could be hypothesised to mediate the effects of sleep on the consolidation of newly learned words in infancy. However, no study has so far tested this hypothesis.

I am designing a study with the aim of exploring the interplay between sleep, babble, and the learning of novel words. The study assesses whether words containing sounds from a child's babble repertoire are retained differently than words without such sounds. This investigation seeks to determine if familiarity with specific speech sounds gained through babble mediates memory and the post-sleep memory benefits on infants' acquisition of new linguistic material. After collecting babble data, I plan to design nonwords for each child, either containing consonants produced in their babble (IN words) or not (OUT words). With a similar design to that employed in the experimental study in this thesis, this study will test whether IN and OUT words show different levels of consolidation in infants who napped shortly after first exposure to the words compared to infants who did not. The answer to this question will shed more light on the combined influence of sleep and existing knowledge on the consolidation of new information. Specifically, it will clarify whether it is unfamiliar or familiar information that is more strongly consolidated during sleep.

What initiated the idea for this study is a post-hoc analysis of the distribution of the word form generalisation performance across the nap and the wake group in the experimental study. This exploratory analysis revealed differences in terms of individual variability. Specifically, word form generalisation performance showed greater variability in the wake than in the nap group (see Figure 1 and Figure 2 below).

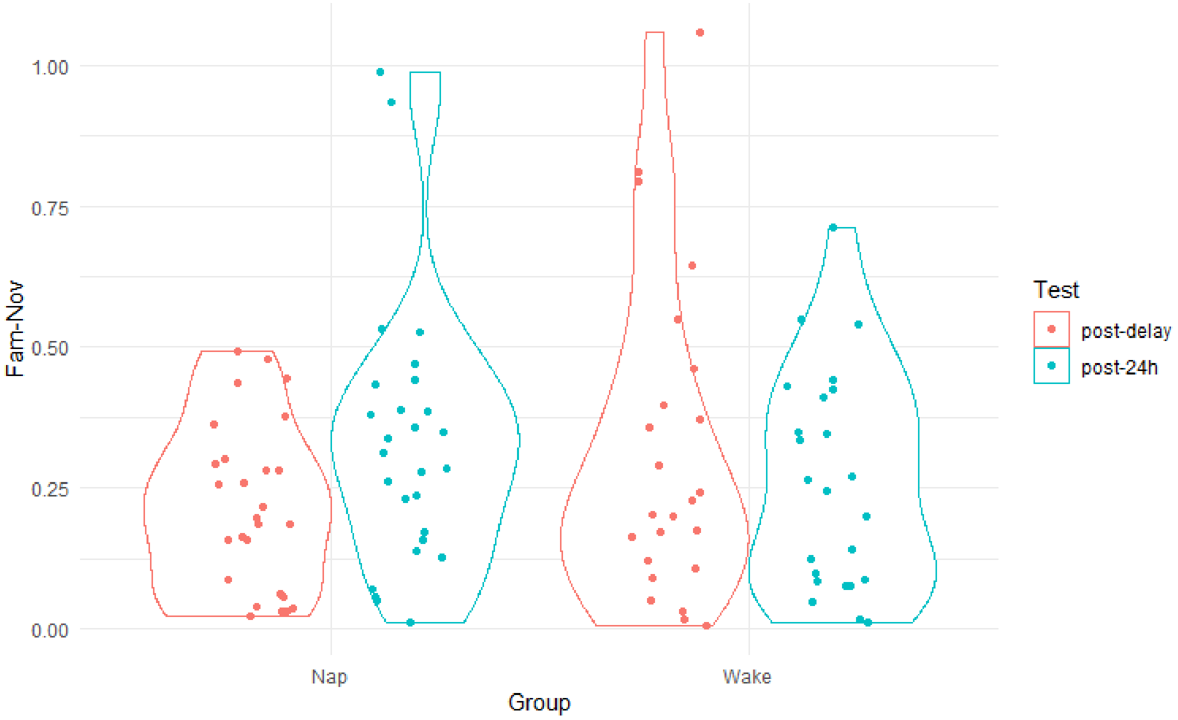

Figure 1. Individual data points per group in each of the two testing sessions. Chance performance is 0.0.

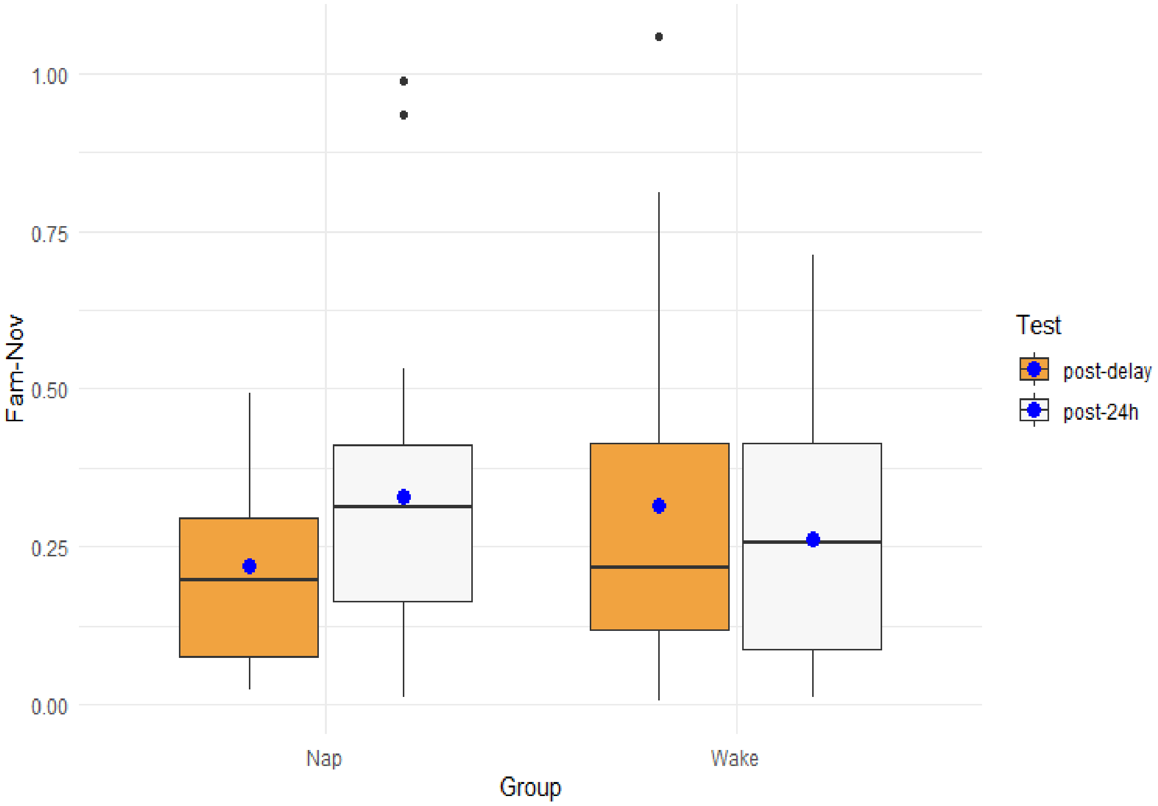

Figure 2. Average recognition performance at each of the two tests by Group. Chance performance is 0.0. The boxplot shows the median as a horizontal line across each box. The blue filled circle inside each box represents the mean.

This finding indicates that some infants in the wake group performed particularly well, even better than infants in the nap group, whereas for others performance was considerably lower. The performance of infants in the nap group was more consistent. These differences could not be directly explained by between-group differences in terms of sample size or age, as these variables did not significantly affect word form generalisation and were not significantly different between groups. Similarly, differences in affective state are unlikely to explain these findings, as children were excluded from the final sample if they showed signs of fussiness, tiredness or inattention. The time of day for each of the three sessions did not statistically differ across groups either. Thus, the two groups might have differed with respect to other variables.

Following further examinations of the video recordings of the Zoom calls, children were found to differ in the amount of babbling behaviour produced in each of the testing sessions (see Figure 3). As explained above, babble has a role in word learning; it mediates infants' attentional resources to speech and scaffolds ongoing language learning. Therefore, babbling may be a factor worth considering in this investigation. A tentative hypothesis would be that children whose babble includes the same consonants as the target words are facilitated in retaining these words, perhaps because they focused more attention on these words.

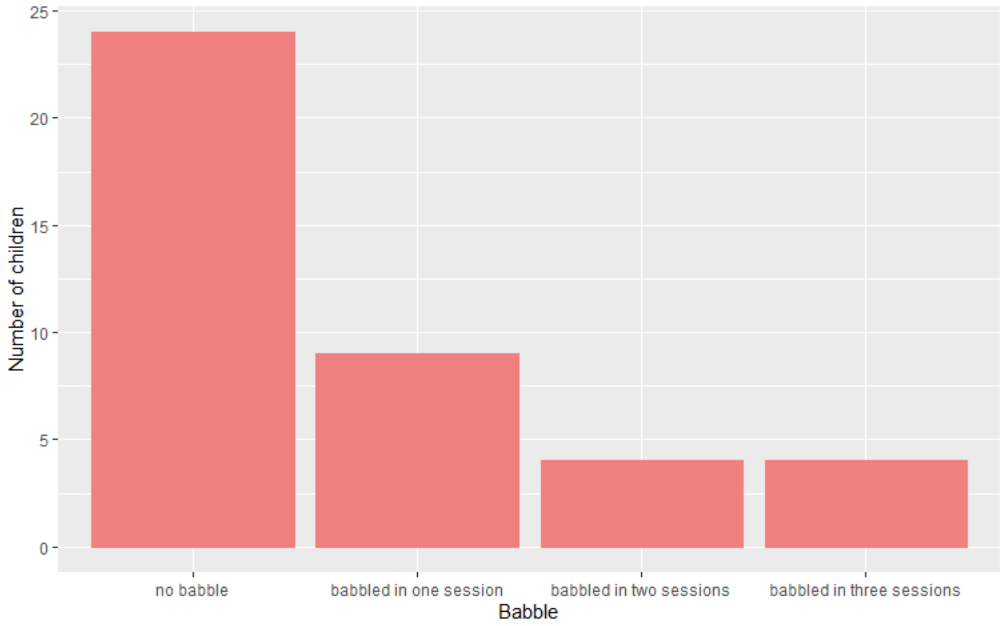

Figure 3. Number of children producing babble and in how many sessions.

Figure 3 shows that few participants babbled in any of the three experimental sessions. This limited our statistical power and excluded in-depth analysis of the influence of babble on word form generalisation. It was not possible to study whether the production of consonants matching those contained in the target words led to better (or worse) encoding, as earlier experimental studies might have suggested (DePaolis, Vihman & Keren-Portnoy, 2011; DePaolis, Vihman & Nakai, 2013; Majorano et al., 2014). However, the babbling profile of the infants involved was further analysed descriptively, to test for the presence of any between-group differences. Figure 4 shows the babbling profile in the nap vs. the wake groups.

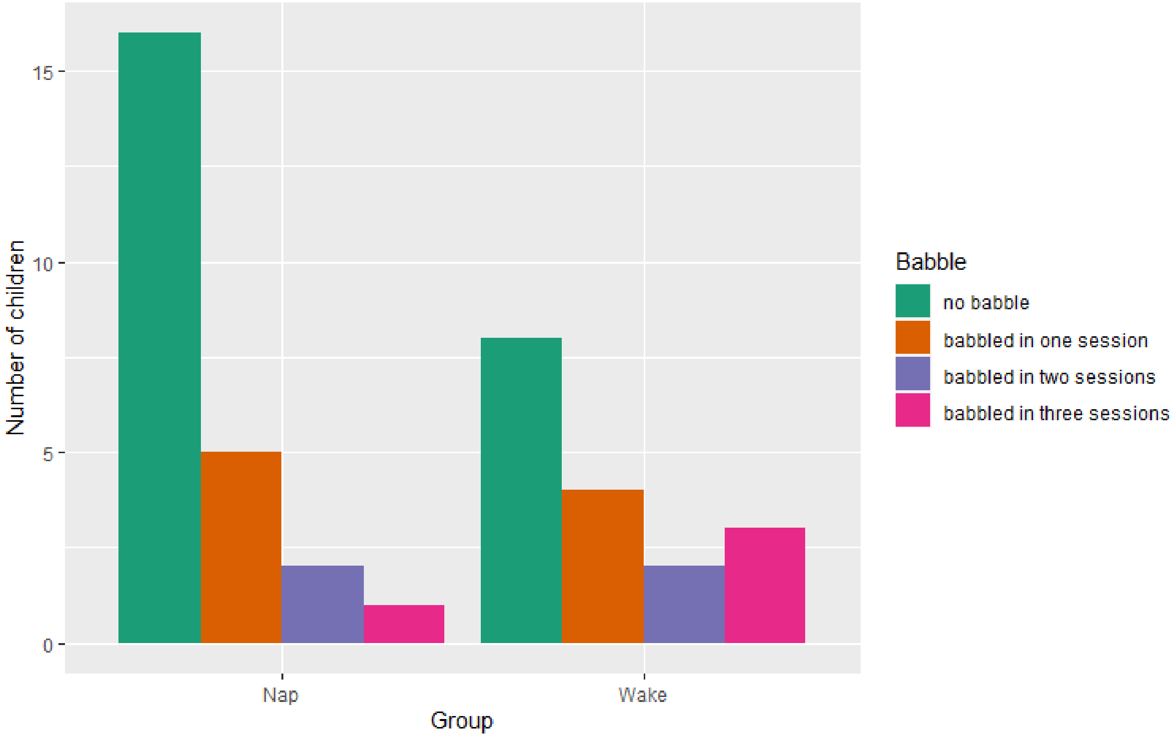

Figure 4. Number of vocalisers per group, in each session.

Figure 4 shows the number of infants in each group who babbled and the number of sessions they babbled in. Descriptively, while the nap group shows a more compact babbling profile, being mainly composed of non-babblers, the wake group displays more variable babbling behaviour. These differences in variability reflect those observed in memory performance between groups, as displayed in Figure 2.

Although the limited sample size precluded any further analysis, babble could be worth investigating in infant consolidation of linguistic information, as it relates to the variability in the word form generalisation data. The findings from the study I am designing will test this hypothesis.

The role of naps and overnight sleep

The three studies conducted here have demonstrated a complex interplay between daytime napping and overnight sleep across the first two years of life. They found that infant sleep is associated with word learning both locally, as demonstrated by associations between post-learning sleep and improved word form generalisation, and longitudinally, as demonstrated by the correlations observed in the questionnaire-based study. In this respect, the relative role of daytime and nighttime sleep on word learning appears to evolve over this period, with daytime sleep being more important before the first birthday as compared to nighttime sleep at later ages.

Although the experimental study found no effects of nap length or of length of time from the familiarisation session to the nap, it supports the suggestion that a combination of daytime and nocturnal sleep might be necessary for word learning in 7.5-month-olds. This is further reinforced by the findings from the questionnaire-based study, which demonstrated that a higher proportion of daytime sleep in relation to nighttime sleep was linked to more advanced vocabulary and motor skill at 7 months. This suggests that, in the early stages of memory development, naps may offer valuable opportunities for initiating the consolidation of new memories, which is then deepened further in the course of subsequent nighttime sleep (Mullally & Maguire, 2014; Riggins & Spencer, 2020). Consequently, the cessation of naps could be associated with development in the child’s memory system, which would enable children to maintain information acquired during the day long enough for it to be consolidated during nighttime sleep (Esterline & Gómez, 2021). Once again, this aligns with the findings from the questionnaire-based study, which revealed that a larger proportion of daytime sleep over nighttime sleep started to have a negative association with vocabulary and locomotion development after the first year of life. This suggests that as infants grow, more consolidated nocturnal sleep may become instrumental for further memory consolidation. This shift in the relative importance of more frequent sleep versus more consolidated sleep over the course of infancy may help explain the mixed findings observed in previous research.

The findings from this thesis suggest interesting directions for future research, particularly in examining the relative significance of more frequent versus more consolidated sleep throughout development. It could be explored to what extent the combination of a post-learning nap and nocturnal sleep is associated with word form generalisation, and other aspects of word learning, in children who no longer nap regularly. To shed light on this issue, future research could adopt a between-subject design with age-matched children, comparing word form generalisation performance of children who habitually nap with those who do not, after a delay spent awake and another inclusive of a daytime nap. While convincing non-habitual nappers to take a nap might represent a challenge, online data collection could be a suitable solution to this end. It would allow children and their families to participate in the study within a more familiar environment, potentially reducing the novelty and the stimulation associated with in-lab experimental settings, which might otherwise interact with the child's ability to fall asleep. Second, future investigations could clarify the factors associated with the abandonment of naps; disentangling endogenous factors from exogenous factors such as cultural habits, family routines and childcare practices may be impossible. Nevertheless, large-scale studies sampling from wide and diverse geographical and demographic backgrounds could clarify what underlies the stabilisation of more prevalent nocturnal sleep in the human infant, independently of exogenous factors. This would help clarify to what extent letting go of naps is an indicator of the development of the memory systems and could inform clinical and childcare practice accordingly. Third, sleeping through the night is largely dependent on emotional regulation, in children and adults alike (Vandekerckhove & Wang, 2018). Aspects of emotional regulation have been associated with quality sleep in infants, as evidenced by more sociable infants with positive mood sleeping longer at night than infants with poorer regulatory capacity (e.g., Atkinson et al., 1995; Spruyt et al., 2008). Several factors may influence infants' temperament and self-regulatory abilities, such as the socioeconomic status (SES) of their household, as early as 6 months of age (Jansen et al., 2009). In Jansen et al. (2009), lower SES was associated with more difficult temperament in infants. SES, in turn, is closely tied to sleep hygiene and with the quality and duration of sleep in infants, with children from poorer SES families experiencing poorer sleep hygiene, shorter sleep duration and more sleep difficulties (El-Sheikh et al., 2013). Detailed investigations should be designed to study the transition to more prevalent nocturnal sleep in households of varying SES backgrounds, with a specific focus on understanding the interplay between emotional regulation, SES (especially in relation to its sub-indicators such as family stress and parental mental health) and bedtime routines on infants' transition away from daytime napping towards more sleep occurring overnight.

Methodological contributions

This thesis pioneered online testing methods for studying preverbal infants. Online research was virtually absent in developmental studies but became more common during the COVID-19 pandemic. Before this study, there were no piloted protocols nor was there technical support for collecting looking time data from preverbal infants online, and there was very little academic literature on the topic. An exception was Lookit, an online platform developed by a team of researchers at MIT (Scott & Schulz, 2017; Scott et al., 2017) that makes it possible to run preferential looking and looking time experiments with infants completely online. However, the use of this platform in the UK was impossible at the time due to GDPR regulations. So, to the best of my knowledge, this thesis presents the first successful attempt at using Zoom in combination with traditional looking time measurement methods for online data collection with young infants, making cross-study comparison easier.

Creating an original online experiment with infants posed unique challenges; the procedures proved to be fundamentally different from research in the lab. First, the experiment required specific ethical considerations for data privacy and participant compensation. Second, the frequent emergence of unforeseen issues exclusive to online testing, such as distractions in participants' home environments and variations in internet speed and webcam quality, required a significantly longer piloting period compared to in-lab experiments, which normally follow well-established and replicable procedures. Despite these difficulties, my study successfully addressed these challenges and established the first looking time data collection protocol for preverbal infants over Zoom, using a platform that is traditionally employed in laboratory settings. This has important implications for future studies interested in conducting online research with infants.

Online data collection, initially a temporary solution to collect data during national lockdowns, offers several advantages to developmental research. Traditional in-lab studies often show an overrepresentation of industrialised, well-educated, and affluent populations, who can easily access developmental labs during regular working hours. In contrast, online testing enables participation from more various demographics and larger samples (Buhrmester, 2018; Lourenco & Tasimi, 2020).

Furthermore, the domestic setting that infants and their caregivers participate from is a more naturalistic environment than the highly controlled setting of developmental laboratories. This enables developmental researchers to study infants within conditions that align more closely with an infant's typical learning circumstances, enhancing the ecological validity of the data collected.

It should be noted that specific technological devices and internet access are almost always required for participating in online studies. For example, the experimental study in this PhD thesis required parents to connect to the call by either a computer or a tablet, which are not yet accessible to all families. The extent to which this study included participants from a wider range of socioeconomic backgrounds compared to in-lab study is accordingly limited. Nevertheless, the accessibility of these devices has significantly improved in recent years, making online research a promising avenue for studying a wider range of infant populations.

Concluding remarks

Infants in the first two years of life exhibit both the largest amount of sleep and the most accelerated transformations in self-awareness and comprehension of the surrounding environment (Thelen & Smith, 1994; Vihman, 2014). These dramatic advances in knowledge are rooted in memory processes, yet only a limited number of studies have investigated aspects of infant development considering how memories are built, strengthened and reorganised. Simultaneously, cognition and language are embedded in a living organism that is grounded in a physical world and interacts with it through a physical body. Therefore, the ways the organism explores and interacts with the environment evolve in parallel with its physical changes. As infants’ motor and sensory systems change during development, their experiences of the world change accordingly. When infants start self-locomoting they can reach and manipulate previously inaccessible objects, they gain new angles through which they can see the environment and they start hearing new linguistic input (Oudgenoeg-Paz et al., 2012). These factors are all highly likely to have an effect on vocabulary development.

In the light of the above, theorising lexical development without considering the development of motor skills or the memory mechanisms that underlie word learning risks providing only a partial picture of the process by which phonological and lexical knowledge are built. This thesis adopted a holistic perspective on development to address this issue. It answered questions related to word learning, taking into account that phonological and lexical knowledge are built from what the child hears and says, from the multi-sensory feedback they receive from other individuals and their own actions, and from the memory processes that consolidate this information (Menn et al., 2013). Thus, the findings of this investigation provide biologically sound insights into how first words are learned, clarifying the memory mechanisms involved in this process and how development in multiple domains (i.e., sleep regulation and self-locomotion) may influence word learning, and unveil promising avenues for future work.

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