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https://doi.org/10.1111/lang.12544

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LANGUAGE LEARNING
A Journal of Research in Language Studies

Language Learning ISSN 0023-8333

SYSTEMATIC REVIEW ARTICLE

Systematic Review of the Effects of Sleep on Memory and Word Learning in Infancy

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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 stabilization and generalization of new word form–meaning associations. Some studies investigated changes in brain responses after word learning and in sleep parameters during postlearning 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

CRediT author statement – **Margherita Belia**: conceptualization; formal analysis; methodology; funding acquisition; investigation; writing – original draft preparation; writing – review & editing. **Tamar Keren-Portnoy**: supervision (equal); writing – review & editing. **Marilyn Vihman**: supervision (equal); writing – review & editing.

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This work was supported by the UK Economic and Social Research Council. The funding source had no specific role in study design, in the collection, analysis and interpretation of data, in the writing of the report, or in the decision to submit the article for publication. We would like to thank Prof. Guillaume Thierry for his insightful comments on a preliminary version of the paper.

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The handling editor for this manuscript was Kara Morgan-Short.

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DOI: 10.1111/lang.12544

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should address these gaps for researchers to better understand lexical development and to create links between memory and language acquisition research.

Keywords sleep; word learning; infants; memory; generalization; language development

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, stabilization and enhancement, and how they are evidenced in development. We then summarize 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 stabilization and enhancement. Stabilization 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 stabilized, 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 generalization (Stickgold & Walker, 2013).

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Item integration is the assimilation of the memory into a network of existing related memories (see Lewis & Durrant, 2011). Multi-item generalization 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 stabilization 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 generalization. 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 familiarized, 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 familiarization, 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 generalized 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 theorized to be responsible for memory consolidation (but see Yonelinas et al., 2019). Specifically, new memories stabilize 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 generalization (Lewis & Durrant, 2011). Several studies have reported a

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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 theorized 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 stabilization 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 hypothesized 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

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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 postlearning 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 stabilization 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 stabilization (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 recognized 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 reorganization 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 postlearning sleep and competition effects between a new

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word form and its neighbors 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, postsleep recall was stronger in children than in adults and for novel words without neighbors than for words with phonological neighbors, suggesting that sleep-dependent memory stabilization 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.,

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2008) and locally in infants' increased facility in acquiring novel words that contain sounds that appear consistently in their vocalizations (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 synthesize 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:

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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) summarized 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.

Method

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

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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).

Publications

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.

Samples

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

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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 organized 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.

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),

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

First author	Year	Participant age (in months)	Title	Journal
Dionne	2011	5.39–62.64	Associations between sleep-wake consolidation and language development in early childhood	*Sleep*
Friedrich	2017	6.00–8.00 ($M = 7.20$)	The sleeping infant brain anticipates development	*Current Biology*
Knowland	2022	6.00–36.00	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	7.73–37.83 (initial assessment)	Frequent daytime naps predict vocabulary growth in early childhood	*Journal of Child Psychology and Psychiatry*
Friederich	2015	9.00–16.00 ($M = 12.20$)	Generalization of word meanings during infant sleep	*Nature Communications*
Friedrich	2019	14.00–16.00 ($M = 15.12$)	The reciprocal relation between sleep and memory in infancy	*Developmental Science*
Friedrich	2020	14.00–17.00 ($M = 15.11$)	Sleep-dependent memory consolidation in infants protects new episodic memories from existing semantic memories	*Nature Communications*

(*Continued*)

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Table 1 (Continued)

First author	Year	Participant age (in months)	Title	Journal
Horváth	2015	16.00	Napping facilitates word learning in early lexical development	*Journal of Sleep Research*
Horváth	2016	16.00	A daytime nap facilitates generalization of word meanings in young toddlers	*Sleep*
He	2020	25.10–29.90 ($M = 26.80$)	Two-year-olds consolidate verb meanings during a nap	*Cognition*
Werchan	2021	29.00–36.00 ($M = 31.43$)	A daytime nap combined with nighttime sleep promotes learning in toddlers	*Journal of Experimental Child Psychology*
Axelsson	2018	29.80	Napping and toddlers' memory for fast-mapped words	*First Language*
Werchan	2014	30.00–35.00 ($M = 32.94$)	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 (*M*s)	Goodnight book: Sleep consolidation improves word learning via storybooks	*Frontiers in Psychology*

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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 summarizes the learning procedures employed in the studies.

As regards testing procedures (see Figure 2), four studies—Friedrich et al. (2015, 2017, 2019, 2020)—employed electrophysiological measures, that is,

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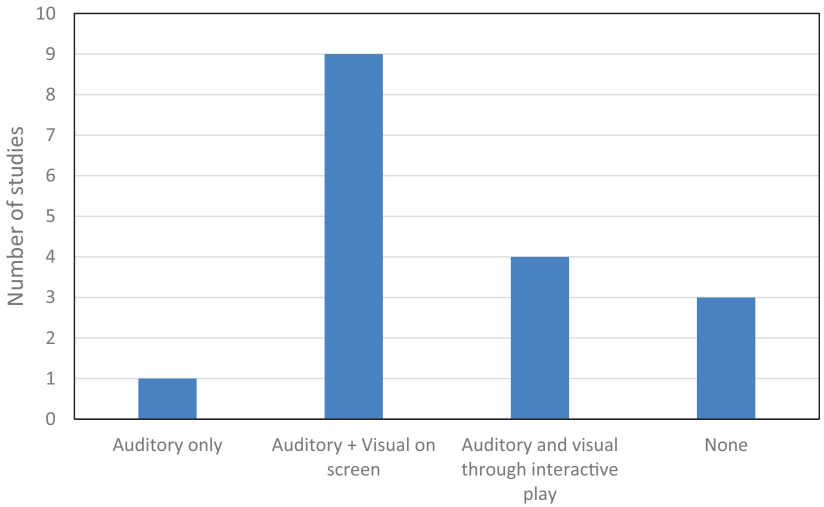

Figure 1 Learning situation.

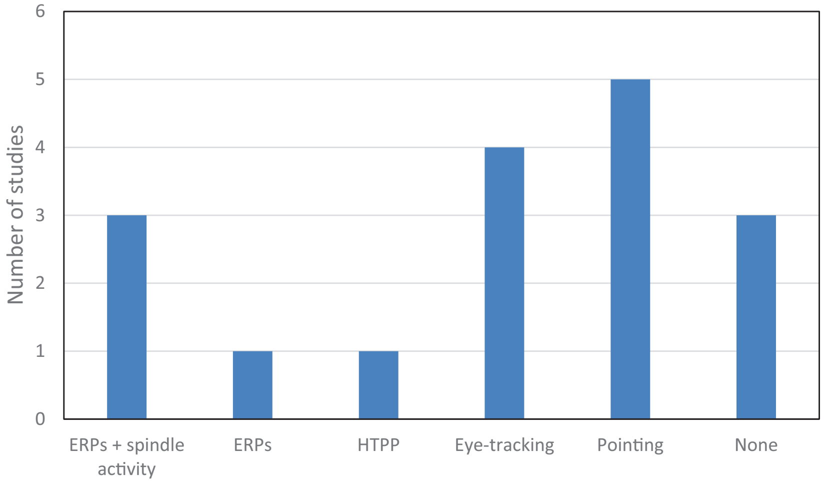

Figure 2 Testing procedures employed. ERP = event-related potential; HTTP = head-turn preference procedure.

event related potential (ERP) responses to stimulus presentation and/or spindle activity during postlearning sleep, nine employed behavioral measures, and three employed surveys—Dionne et al. (2011), Horváth and Plunkett (2016),

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and Knowland et al. (2022). Among the behavioral studies, the measures employed were the head-turn preference procedure (Simon et al., 2017), eye-tracking (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.

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 familiarization 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 postencoding 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 Stabilization: Veridical Memory for New Word Form–Meaning Associations

Another line of research has investigated the effects of sleep on the stabilization 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

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napped during the delay recognized the new associations after the postlearning nap (as signaled 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

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Table 2 Summary table: Studies of veridical memory of word–meaning pairs

Characteristic	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	1. Immediate 2. 1.5 hr after learning	1. 4 hr after learning	1. Active learning 2. Immediate 3. 4 hr after learning 4. 24 hr after learning	1. Immediate 2. 2.5 hr after learning 3. 24 hr after learning 4. 7 days after learning
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

(*Continued*)

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Table 2 (Continued)

Characteristic	Horváth (2015)	He (2020)	Axelsson (2018)	Williams (2014)
Highlights	- Postlearning 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 stabilized 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 after learning test.

Note. “Yes” and “No” indicate significant and nonsignificant differences between the groups’ performances, respectively. Symbol > signals better performance by the group to the left of the symbol.

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provides a summary of the studies of veridical memory of word–meaning pairs.

Generalization 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 generalization of word meanings. In these studies, children were familiarized with novel words and their referents and then tested on their ability to generalize 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 generalized 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 generalized 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 generalize 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

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they had been familiarized but showed an increased N400 effect for words paired incorrectly with both familiarized and novel objects relative to correct pairs, showing that they had lexical–semantic representations for those words. However, infants who had a postencoding nap showed an increased N400 for words incorrectly paired with novel (but not familiarized) 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 familiarized. Furthermore, spindle activity during the postencoding nap was positively associated with this effect (but not with the N400 effect).

Three other studies investigated generalization of word–meaning pairs from a behavioral point of view. Horváth et al. (2016) observed that only children who napped after being familiarized 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 generalization 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 familiarization) was tested in another pointing test where both habitual and nonhabitual nappers showed immediate veridical memory but no evidence of generalization shortly after learning.

In Werchan and Gómez's (2014) study, children (aged 2.5 years) who remained awake in the postlearning 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 generalization 24 hours

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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 generalization of word–meaning pairs.

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 nonnappers' performance, expressive (but not receptive) vocabulary size was strongly and positively associated with memory improvement from immediate to postsleep test in nappers. Friedrich et al. (2019) found a modulating effect of existing knowledge over spindle activity and postlearning memory improvement. In their study that investigated category learning, number and density of sleep spindles in postencoding naps of 14- to 16-month-olds were significantly larger in the postlearning phase (i.e.,

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Table 3 Summary table: Studies of generalization of word–meaning pairs

Characteristic	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. nighttime-sleep group (napping habits not reported)
Number of tests & how long after learning	1. 1.5 hr after learning	1. Immediate 2. 2 hr after learning	1. Immediate 2. 4 hr after learning	1. 24 hr after learning (Exp. 1) 2. 2–3 min (Exp. 2)	1. 0.5–2.0 hr after learning	1. 24 hr after learning 2. 4 hr after learning (for nap-control only) 3. 4 hr after waking up in the morning (nighttime–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 > nighttime-sleep)
Highlights	- Nappers recognized (N200–N500) and generalized (N400) the word-meaning pairs, the wake group did not; - Spindle activity in the postlearning nap positively correlated with generalization.	- A nap improved nappers' generalization; - Wake groups' performance remained unchanged.	- Wake group showed better generalization 4 hr 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 generalization 24 hr later, regardless of napping habits; - Nocturnal sleep alone is insufficient to generalize verb meanings, regardless of napping habits; - No generalization observed shortly after learning.	- Nappers showed episodic memory for familiarized word-object pairs but no semantic processing; - Spindle activity in postlearning nap positively correlated with N200–N500-like effect but not N400; - Wake group showed semantic processing of both new and familiarized pairs.	- Nappers generalized the category labels 24 hr after learning; - No generalization was observed after a single nap or a single night of sleep; - Longer postlearning wake periods could decrease performance.

Note. "Yes" and "No" indicate significant and nonsignificant differences between the groups' performances, respectively. Symbol > signals better performance by the group to the left of the symbol.

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after learning previously unknown words) than after a nonlearning 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 postencoding nap predict greater memory generalization improvement on the next day, but it was stronger in those infants who did not show generalization during encoding compared to a subgroup of infants who had already showed signs of generalization at encoding before sleep. However, even in this latter subgroup, spindle density was a better predictor of postlearning generalization of word–object pairings than were presleep generalization 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 generalization 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 hypothesized that longer nonrapid 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 generalization of word meanings at the category level.

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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 analyze 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 behavioral 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, nonnappers' 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 stabilization could have oc-

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curred. 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 generalization 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 generalization 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, Kurdziel, & Spencer, 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 stabilization, 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 generalization. Sleep-associated extraction of the shared fea-

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tures across multiple referents (Konrad et al., 2016) also underlies the generalization 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 generalization of word meanings, multi-item generalization 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 familiarization, indicating an interesting direction for future research. We are now running a study to investigate whether infant sleep supports the generalization 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 generalization 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 postencoding 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.

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A phenomenon parallel to multi-item generalization 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 characterized 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 &

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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 postencoding 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 stabilization 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 postlearning 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 neighbors but that postsleep effects on the stabilization 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.

Existing lexical–semantic knowledge was also found to mediate postsleep memory processing by Friedrich et al. (2020). In their study, postnap neural correlates revealed episodic memory, but not semantic processing, for the familiarized pairings. An N400 effect was present in nappers in response to the object categories incorrectly paired with unfamiliarized referents but not with incorrectly paired familiarized 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 postencoding nap recognition of the specific familiarized referents as members of known lexical categories (signaled by an effect like the N200–N500) might have been temporarily prioritized over more generalized lexical–semantic processing of the stimuli. Prioritizing the stabilization 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

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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 nonlanguage 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 behavioral 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 generalize 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

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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 behavior 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 nonhabitual 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 nonhabitual 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 postlearning nap as regards memory, suggesting that they may have had more efficient nap-dependent memory consolidation than had nonhabitual 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 nonhabitual 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 postnocturnal sleep). As nonhabitual 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

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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 nonhabitual 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 labor-intensive, they could be facilitated by remote data collection procedures that might be more child- and parent-friendly. For example, nonhabitual nappers might more readily nap at home than in the lab.

Werchan and Gómez (2014) found better generalization of new category labels in toddlers after a wake interval than following napping. Werchan and Gómez thus hypothesized that generalization 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' generalization as observed 24 hours instead of 4 hours after learning. In this study, the toddlers did generalize 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 generalization, which was observed only after both a postlearning 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 generalization. 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 generalization 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 generalization 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, more-

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over, that dynamic systems theory predicts periods of stability and instability in behavior across development, with instability often being associated with moments of marked behavioral transition (Thelen & Smith, 1994). Thus, the great variability and idiosyncrasy of sleep behaviors 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.

Conclusion

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 behaviors as well as the fast rate at which they learn their language.

Final revised version accepted 3 September 2022

Note

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.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Accessible Summary

Appendix S1. The Systematic Review Process in Detail.

Appendix S2. Methodological Overview of the Studies.

Appendix S3. Details About the Design, Procedures and Results of the Studies Reviewed.

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