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Authors: Emma James, M.Gareth Gaskell, Anna Weighall, Lisa Henderson

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Consolidation of vocabulary during sleep: the rich get richer?

Emma James[a], M. Gareth Gaskell[a], Anna Weighall[b], Lisa Henderson[a]

[a]Department of Psychology, University of York, York, YO10 5DD, United Kingdom

[b]School of Psychology, University of Leeds, Leeds, LS2 9JT, United Kingdom

Corresponding author: Lisa Henderson

Email: lisa-marie.henderson@york.ac.uk

Phone: +44 (0)1904 324362

Address: Department of Psychology, University of York, York, YO10 5DD, United Kingdom

Highlights

- Different neural mechanisms may support word learning in children and adults.
- Children show larger proportions of slow-wave sleep that supports consolidation.
- Consolidation in adults can benefit from richer existing knowledge.
- Meta-analysis suggests extant vocabulary is associated with new word consolidation.
- Directions for uncovering prior knowledge influences on consolidation are proposed.

Abstract

Sleep plays a role in strengthening new words and integrating them with existing vocabulary knowledge, consistent with neural models of learning in which sleep supports hippocampal transfer to neocortical memory. Such models are based on adult research, yet neural maturation may mean that the mechanisms supporting word learning vary across development. Here, we propose a model in which children may capitalise on larger amounts of slow-wave sleep to support a greater demand on learning and neural reorganisation, whereas adults may benefit from a richer knowledge base to support consolidation. Such an argument is reinforced by the well-reported "Matthew effect", whereby rich vocabulary knowledge is associated with better acquisition of new vocabulary. We present a meta-analysis that supports this association between children's existing vocabulary knowledge and their integration of new words overnight. Whilst multiple mechanisms likely contribute to vocabulary consolidation and neural reorganisation across the lifespan, we propose that contributions of existing knowledge should be rigorously examined in developmental studies. Such research has potential to greatly enhance neural models of learning.

Keywords: Word learning; Matthew effect; Memory consolidation; Sleep; Prior knowledge; Brain development; Children

1. Introduction

Building a good vocabulary is a crucial task for the developing child, enabling successful communication with others in both spoken and written language. A poor vocabulary places constraints on understanding academic texts, thereby hindering success at school across a broad range of subjects (Biemiller, 2006). Unfortunately, early vocabulary deficits may not be easy to resolve: a long-standing hypothesis in literacy development is the existence of a *Matthew effect* (Stanovich, 1986). The theory holds that the 'rich' get 'richer' in literacy skills; children with better reading and language skills are equipped to further improve these skills, whereas struggling children progress at a slower rate. Although longitudinal studies have provided mixed evidence for Matthew effects in literacy (e.g., Scarborough, Catts, & Kamhi, 2005), some of the most convincing evidence has come from the domain of vocabulary, where the knowledge gap widens throughout the school years (Cain & Oakhill, 2011). Discovering the mechanisms underlying this developmental lag is a key challenge for language acquisition researchers if we are to understand how best to help prevent increasingly widespread problems for children with vocabulary difficulties.

Studies of Matthew effects have largely focused on reading experience and exposure as the underlying mechanism: children with better literacy skills enjoy reading more, will engage in literacy activities in their own time, and have the skills to learn new words from texts when doing so (Cain & Oakhill, 2011; Stanovich, 1993). However, when viewing word learning in the context of neurocognitive theories of memory (Davis & Gaskell, 2009; Wojcik, 2013), it is plausible that other non-environmental processes might also contribute to the effect. Davis and Gaskell (2009) applied the Complementary Learning Systems (CLS) framework (McClelland, McNaughton, & O'Reilly, 1995) to word learning, hypothesising that a new word is initially stored as a distinct episodic trace in the hippocampus, but becomes integrated with existing vocabulary in neocortical long-term memory over time, particularly during sleep. In the broader memory literature, prior knowledge has been shown to enhance the ease with which new information is integrated, and initial evidence suggests that this may also be the case for the overnight integration of newly learned words in childhood (Henderson et al., 2015; Horváth, Myers, Foster, & Plunkett, 2015b). Weaker vocabulary may therefore hinder further vocabulary development by constraining neocortical consolidation, as well as via limiting an individual's exposure to language.

If existing knowledge plays such an influential role in subsequent vocabulary learning, then how is it that children (who typically have limited levels of vocabulary knowledge relative to adults) are able to accumulate a mass of vocabulary knowledge at such a rapid rate? Here, we consider that different states of brain maturation elicit different mechanisms to support word learning. Namely, we will review evidence suggesting that whilst word learning in the adult system can benefit from enriched levels of existing knowledge, the sleep architecture of the typically developing system is optimised for sleep-associated memory consolidation. We will begin by summarising systems consolidation models of memory and applications to word learning across development, and review studies that directly compare consolidation processes in children and adults. We consider the proposal that prior knowledge can account for inconsistencies in these data, and present a meta-analysis of our own published data that supports a relationship between existing vocabulary knowledge and the consolidation of newly learned words. Finally, we will propose future directions for addressing the consolidation account of Matthew effects.

2. Systems consolidation and the role of sleep

It is well accepted that memory is not a unitary store in which all information is stored and accessed in the way it was initially encoded (McGaugh, 2000).

Although the hippocampus and other regions of the medial temporal lobes are known to play crucial roles in memory, studies of patients with hippocampal damage demonstrated that individuals could retain some memory of earlier life experiences (e.g., Scoville & Milner, 1957). From this, it has been concluded that memories may become gradually independent of the hippocampal system over time (Squire & Alvarez, 1995; Squire & Zola-Morgan, 1991) via a process coined *systems consolidation.* Although the nature of the different memory systems and the mechanisms that enable their interaction remain hotly debated in memory research (e.g., Nadel, Winocur, Ryan, & Moscovitch, 2007), there is good evidence to suggest that memory reorganisation continues for the months and even years after first encountering new information (e.g., Takashima et al., 2006).

The time required for systems consolidation necessarily includes multiple opportunities for sleep, and evidence is now converging on the view that neural processes that occur during sleep actually play an active role in memory consolidation. In particular, a substantial body of research has focused on the role slow-wave sleep (SWS) in various aspects of declarative memory consolidation (e.g., Marshall & Born, 2007), suggesting that this stage of sleep enables the reactivation of hippocampal traces to promote slower learning and integration in the neocortex (Diekelmann & Born, 2010; Rasch & Born, 2013). In this section, we describe the key features of SWS and other related aspects of sleep architecture, before reviewing the evidence for its involvement in consolidating linguistic information.

2.1. Slow-wave sleep (SWS) and memory

SWS (non-rapid eye movement stages 3 and 4) is characterised by three components of sleep architecture: slow oscillations, spindles, and ripples. Slow oscillations are alternating states of widespread hyperpolarisation and depolarisation at approximately 0.8 Hz. This synchronous firing of neurons throughout the brain is thought to enable communication between hippocampal and neocortical systems (Marshall & Born, 2007; Sirota & Buzsáki, 2005). The hyperpolarised "up" states of slow oscillations feature sleep spindles: short bursts of ~10-15 Hz activity (also seen in Stage 2 sleep). These too have been linked to the communication and replay of information between memory systems, given their tight temporal relationship with cortically-driven slow oscillations and hippocampal activity (Sirota & Buzsáki, 2005). The third component - although one not detected by surface EEG – involves very fast bursts of 80-100 Hz activity originating from the hippocampus. Recent intracranial recordings by Staresina et al. (2015) have demonstrated that these hippocampal ripples are further nested within the troughs of spindles, providing evidence that ripples, spindles, and slow oscillations occur systematically together during SWS. Cross-regional coupling between hippocampal and neocortical measurements demonstrated that the phase of slower oscillations modulated the power of faster oscillations: hippocampal spindles increased in relation to cortically recorded slow oscillations, and hippocampal ripples increased in relation to cortical spindles. The authors concluded that this functional coupling hierarchy might subserve the transfer of information between hippocampal and neocortical memory systems during consolidation.

In support of a causal role for slow oscillations in coordinating memory processing, studies have shown that boosting slow oscillation activity using transcranial direct current stimulation during sleep can improve declarative memory retention (Marshall, Helgadóttir, Mölle, & Born, 2006). However, the relationship between slow oscillations and memory consolidation is likely to be bidirectional: a number of studies have also linked learning demands to neural activity during subsequent sleep (Mölle, Eschenko, Gais, Sara, & Born, 2009). For example, both SWS coherence (Mölle, Marshall, Gais, & Born, 2004) and spindle density (Gais, Mölle, Helms, & Born, 2002) have been shown to be increased in sleep following a word pair learning task compared to a visual processing task of equivalent visual input and duration. Converging evidence therefore suggests that sleep plays a reciprocal and important role in the learning and retention of new information.

2.2. A Complementary Learning Systems (CLS) account of word learning

Dual systems approaches to memory and consolidation have been of particular interest to language researchers in considering apparent dissociations in performance in explicit and implicit measures of word learning (e.g., Henderson et al., 2014). In particular, the Complementary Learning Systems account has provided a useful framework in which to consider these differences (Davis & Gaskell, 2009). According to the CLS model of memory (McClelland, 2013; McClelland et al., 1995), the two memory systems feature different types of representation: the neocortical memory system consists of overlapping representations that are susceptible to spreading activation from incoming information, whereas the hippocampal system forms sparse memory representations that retain their specificity to the contexts in which they are learned, and are stored largely independently of other representations in memory. However, reinstatement of these hippocampal representations into the neocortex enables this new episodic information to become gradually incorporated into the neocortical system via re-experiencing, rehearsal, or sleep processes. This computational model of memory was proposed to account for the way in which the learning brain can protect existing knowledge from the possible interference of new information, yet remain plastic to new skills and information.

The CLS model thus provides a framework in which to consider how a language system can come to process known words with high speed and efficiency, and function despite substantial variation in the incoming speech signal (Davis & Gaskell, 2009). Much like the distributed representations featured in the CLS account of memory, some computational models of spoken word processing propose that automatic spoken word recognition is accomplished by a distributed system in which phonological and semantic information is stored separately but activated in parallel as speech input unfolds (Gaskell & Marslen-Wilson, 1997). In line with this view, studies suggest that incoming speech sounds initiate phonological competition among related word level representations until the word has been fully specified (Mattys & Clark, 2002). At a semantic level, recent work suggests that activation of a given word also results in the sustained activation of related words in order to facilitate continued language processing and comprehension (e.g., Rodd, Cutrin, Kirsch, Millar, & Davis, 2013). The lexicon is thus characterised as a highly interconnected system that enables the rapid processing of linguistic information for successful communication.

To become an established lexical entry, a new word must become “engaged” with this existing lexicon (Leach & Samuel, 2007) without causing disruption to the system. The CLS framework proposes that an initial encounter with a new word engages numerous cortical regions involved in speech processing that output to form a bound representation in the hippocampus. Initially, retrieving the meaning and phonological form of this new word requires hippocampal mediation, but this new word can become gradually integrated into the main neocortical recognition system over longer periods of time – particularly during sleep (Davis & Gaskell, 2009). A key prediction of this model is therefore that we should not see immediate automatic competition and priming effects for newly learned words, but that these key markers of a fully-fledged lexical item should emerge over longer periods of time (including sleep) as representations become integrated into a distributed system. Although abstracting and generalising linguistic information (as in the context of grammatical features) may be feasible from newly acquired hippocampal traces (Kumaran & McClelland, 2012), the automaticity with which this occurs should be enhanced after representations become integrated within the neocortex. A wealth of evidence now exists to suggest widespread benefits for sleep for the memory and processing of newly acquired language. These have been demonstrated across phonological (Dumay & Gaskell, 2007), semantic (Tham, Lindsay, & Gaskell, 2015) and grammatical domains (Nieuwenhuis, Folia, Forkstam, Jensen, & Petersson, 2013). Less attention has been given to the orthographic aspects of word learning in this area, particularly in developmental research, which limits our discussion of written language here (see Bakker, Takashima, van Hell, Janzen, & McQueen, 2014, for consolidation effects across spoken and written modalities).

Studies of spoken word learning have often examined declarative aspects of learning – i.e., the explicit recall of a word form. For instance, in novel word training studies, adults show an increase in the number of word forms they can successfully recall following a period of sleep, whereas no such increase is seen during an equivalent period of wake (Dumay & Gaskell, 2007). Gais, Lucas, and Born (2006) examined this from the perspective of foreign language learning, training native English adults on German vocabulary translations. Participants recalled more words when they slept shortly after learning compared to when they remained awake.

Comparing sleep versus wake periods in behavioural paradigms thus supports that sleep can strengthen word representations for successful retrieval. Tamminen, Payne, Stickgold, Wamsley, and Gaskell (2010) used polysomnography to further specify that the overnight strengthening of word form representations – in this case indicated by improvements in a speeded recognition task - is associated with the amount of time participants spent in SWS.

Researchers have addressed the causal role for sleep in word form consolidation by experimentally manipulating memory reactivations during sleep. Targeted memory reactivation (TMR) paradigms replay previously associated sound cues to participants during SWS, under the assumption that this reactivates the individual memory traces from learning and thereby facilitates consolidation (see Schreiner & Rasch, 2016, for a review). Schreiner and colleagues have demonstrated that recall of newly learned foreign vocabulary translations can be improved by cueing and reactivating newly learned words during SWS (compared to recall of uncued translations; Schreiner & Rasch, 2014) but not during wake (Schreiner & Rasch, 2015). Cues presented during sleep were often followed by slow oscillations, and resulted in increased theta and spindle activity for successful cues only (Schreiner, Lehmann, & Rasch, 2015). Consistent with the findings from Staresina et al. (2015) above, the authors suggested that slow oscillations may provide the temporal framework for stabilization processes to occur. Considered together, these behavioural, polysomnography, and TMR studies provide strong evidence for sleep processes in declarative aspects of language learning.

Studies have demonstrated that sleep is also important for the more implicit aspects of phonological word learning; key to the predictions of the CLS model, sleep has been shown to enhance the integration of a novel word form with existing vocabulary knowledge. According to distributed models of the lexicon (Gaskell & Marslen-Wilson, 1997), a fully lexicalised or “engaged” (Leach & Samuel, 2007) word form can better interact with other entries in vocabulary, competing for activation during word processing. The CLS model predicts that this lexical competition primarily occurs after a period of consolidation, once the word has become integrated within the neocortical memory system. Clear evidence for lexical integration has been provided by studies that teach participants novel competitors (e.g., *cathedruke*) for existing word forms (e.g., *cathedral*) and show that participants become significantly slower to detect a pause inserted into the existing word form (versus detecting pauses inserted into control words for which no new competitor has been taught). Crucially, this slowing of response times does not occur immediately, but emerges after a longer time period if it is inclusive of sleep (Dumay & Gaskell, 2007; Dumay et al., 2004). These findings lend support to the proposal that a period of offline consolidation can enable a word to become integrated with existing vocabulary knowledge and compete during lexical processing (although competition effects between new and existing words have been demonstrated immediately after learning under certain circumstances; see Section 4.1 or McMurray, Kapnoula, and Gaskell (2016) for a discussion). Sleep recordings have demonstrated that larger overnight increases in lexical competition effects between novel and existing words are associated with greater levels of spindle activity during sleep (Tamminen et al., 2010). Consistent with the CLS proposal that consolidation strengthens cortical networks, Davis, Di Betta, Macdonald, and Gaskell (2009) used fMRI to demonstrate that words learned a day prior to scanning had become more independent of the hippocampus during retrieval than words learned the same day: words with the opportunity for sleep-associated consolidation processes to occur elicited greater neocortical activity (e.g., in the superior temporal gyrus) and reduced engagement of the hippocampus compared to unconsolidated words. The converging evidence therefore supports that sleep both strengthens new word forms, and enables systems consolidation processes to integrate new words with existing knowledge.

Other research has examined semantic and grammatical aspects of word learning, with support beginning to accumulate for a role of sleep in these domains. One approach has been to examine the emergence of interference effects caused by the automatic activation of semantic information. Clay, Bowers, Davis, and Hanley (2007) used a picture-word interference task in which picture naming slows in the presence of distractor words, particularly for words that are semantically related. This latter meaning-specific effect was not apparent for novel words immediately after learning, but emerged one week later. Similarly, Tham et al. (2015) showed that a semantic incongruency effect for newly learned words emerged only after a period of sleep (e.g., participants took longer to decide that a Malay translation of “fox” was bigger than a Malay translation of “bee” when the latter was presented in larger font). Consistent with sleep effects for phonological forms, the integration of semantic information has also been linked to both SWS duration (Tham et al., 2015) and spindle activity in the intervening night (Tamminen, Lambon Ralph, & Lewis, 2013; Tham et al., 2015).

The CLS model predicts that transfer of newly formed memory traces to the neocortex should facilitate the abstraction of linguistic regularities (e.g., grammatical properties) in a more automatic fashion as the memory traces become represented in a more distributed manner. Speaking to this hypothesis, sleep-associated consolidation has been demonstrated as particularly important when rules are presented only implicitly during the learning phase (Batterink, Oudiette, Reber, &

Paller, 2014; Nieuwenhuis et al., 2013; Tamminen, Davis, Merkx, & Rastle, 2012) or when speeded access is required in generalising to new exemplars (Tamminen et al., 2012). For example, using a nap paradigm with a stimulus set in which novel prefixes predicted the animacy of existing referents, Batterink et al. (2014) reported fast learning of the rule made explicit during training, which was not further influenced by sleep. However, adults' ability to extract the hidden regularities in a speeded categorisation task improved after a nap, and was associated with the interaction between SWS and rapid eye-movement sleep. A recent TMR study further supported this role of sleep, demonstrating that auditory cues presented during SWS (Batterink & Paller, 2015) resulted in improvements in generalising grammatical rules.

However, evidence for the role of sleep on the abstraction and generalisation of new linguistic information is mixed, and this may be partially due to the nature of the mappings to be learned. While the CLS account of word learning predicts that neocortical integration should facilitate the abstraction of rules, it also predicts that the learning of arbitrary mappings is more dependent on hippocampal mechanisms and thus greater influenced by subsequent sleep than systematic elements. Mirković and Gaskell (2016) tested this hypothesis by using both arbitrary elements (i.e., word-stem to picture mappings, e.g., *scoiff*-ballerina, *jor*-cowboy) and a more systematic element in the mapping between determiners/suffixes and common semantic features (e.g., *tib…esh/eem* and female; *ked…ool/aff* and male). Knowledge of the arbitrary stems improved for participants who took a nap, whereas – in contrast to the previous findings - the systematic grammatical aspects did not. Mirkovic and Gaskell (2016) suggested that arbitrary items may take priority early in consolidation processes, whereas systematic mappings may be later strengthened.

The extent to which the grammatical mappings overlapped with existing mappings was also higher in this study as gender is a relatively salient feature in English language. This overlap may have facilitated neocortical integration, and thereby reduced the potential boost from sleep (see Section 4).

The extant evidence therefore suggests that sleep has widespread benefits in adult language learning, with the nature of the material to be learned influencing the extent to which sleep supports learning. Polysomnography recordings highlight that both time spent in SWS (and/or slow oscillation activity) and sleep spindles are associated with the explicit recall of new words and with integrating these words with existing knowledge to enable fast and efficient linguistic processing, especially in the spoken domain. What determines the involvement of sleep spindles and/or SWS duration in processes of language consolidation in the above studies remains an important question that future research should aim to untangle. However, considering recent evidence demonstrating the tight temporal coupling of spindles with other oscillations during SWS (Staresina et al., 2015; see Section 2.1), both are considered relevant in the present review, and these sleep-associated consolidation processes are a prime focus in considering language learning across development.

2.3. Consolidation of vocabulary earlier in development

An important theoretical question is whether sleep-associated consolidation processes are equally as – or even more – important during development, given the high demand on fast and efficient vocabulary acquisition in childhood. Interestingly, children show a much higher percentage of SWS than adults (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004) and greater slow oscillation activity that reaches a peak at roughly 10-12 years (Feinberg & Campbell, 2010). Thus, it is plausible that sleep could support the enhanced rates of vocabulary learning earlier in development. First, we review the evidence for sleep-associated improvements in children's language learning, and will later consider how their enhanced levels of SWS might affect processes of consolidation across development (Section 3).

Thus far behavioural evidence suggests that there are indeed similar benefits of sleep for word learning and integration from infancy to adolescence. A number of studies have suggested similar overnight improvements in novel word form learning to those found in adults. For example, Ashworth, Hill, Karmiloff-Smith, and Dimitriou (2014) taught 6- to 12-year-old children novel names for animals, and found a 14 per cent improvement in recall after a period of sleep compared to wake. A 28 per cent overnight improvement compared for novel word recall was demonstrated in a similar age group by Henderson et al. (2012), who also demonstrated that sleep enabled lexical competition to occur in a pause detection tasks (e.g., Dumay & Gaskell, 2007; see Box 1 for more details); no such improvements in recall or lexical competition were apparent across a period of wake.

Moving beyond behavioural findings, only one study to date has utilised polysomnography recordings to examine associations between sleep and vocabulary consolidation in school-aged children: Smith et al. (submitted) demonstrated that slow-wave activity (the power of EEG activity in the 0.5-4 Hz range; SWA) predicted overnight improvements in cued novel word recall in typically developing children (e.g., "Which novel word began with "bisc"?", answer "biscal"). Sleep spindle activity was also associated with these overnight improvements, but was more strongly predictive of the overnight changes in lexical competition (as measured via the pause detection task). These findings are consistent with those of adult studies (i.e., Tamminen et al., 2010), providing initial evidence of similar underlying mechanisms to sleep-associated consolidation of language across development. Although there is a scarcity of work examining sleep-associated semantic integration in children, benefits in consolidation processes have been shown for training word forms alongside their meaning, and thus for the acquisition of a more complete lexical representation. Henderson et al. (2013b) showed that training on new words with their meaning led to better longer term representations of their word forms compared to form-only training in 5- to 9-year-old children. Furthermore, the benefits of a consolidation period for word learning (for both explicit measures of recall/recognition and implicit measures of lexical competition) are apparent even when novel words are more naturalistically encountered within a story (Henderson et al., 2015; Williams & Horst, 2014), demonstrating that these mechanisms are not restricted to explicit training methods and are likely representative of everyday word learning processes (although see Fernandes, Kolinsky, & Ventura, 2009).

The sleeping brain also appears able to abstract and integrate information from learned words from an early age, relevant for both semantic and grammatical aspects of word learning. For example, Friedrich, Wilhelm, Born, and Friederici (2015) used EEG and event-related potentials as a measure of semantic word learning in infants. Infants that napped after learning new words retained an understanding of the specific word meanings, and also generalised these word meanings to novel exemplars. Infants who stayed awake over this interval showed no such markers of learning. Even at this early age, ability to generalise to new exemplars was correlated with sleep spindles during the nap, suggesting that similar mechanisms may be at play in word learning throughout development (see also Horváth, Liu, & Plunkett, 2015a; but Werchan & Gómez, 2014, for conflicting findings). Furthermore, sleep has been shown to benefit the abstraction of statistical regularities in strings of nonsense syllables in infants (Gómez, Bootzin, & Nadel, 2006; Hupbach, Gomez, Bootzin, & Nadel, 2009), suggesting that sleep may aid grammatical learning and consolidation from very early in child development.

3. Consolidation processes across development

A critical first step in interpreting the mechanisms underlying consolidation during development is to assess whether consolidation takes place via a similar systems transfer of information as in adults. In one of the few studies to test the underlying neural mechanisms in children, Urbain et al. (2016) found that hippocampal activity (measured via magnetoencephalography) during the successful immediate recall of new objects positively correlated with percentage of SWS in a subsequent nap in 8-12-year-olds. After sleep however, successful recall was *negatively* correlated with hippocampal activity, and was instead associated with higher activity in the prefrontal cortex. This study suggests that – as in adults – sleep plays a role in transferring newly acquired memory traces from the hippocampus to neocortical regions, and thus that these mechanisms are of interest across development.

While developmental studies have largely provided findings that are conceptually consistent with adult models of sleep-associated consolidation, more careful developmental comparisons have the potential to inform us about the processes involved (Wilhelm, Prehn-Kristensen, & Born, 2012). Children require more sleep than adults overall, and show a much higher percentage of SWS (e.g., ~40% of total sleep time) relative to adults (e.g., ~20% of total sleep time; Wilhelm et al., 2013) that gradually declines throughout adolescence (Jenni & Carskadon, 2004; Ohayon et al., 2004). These changes in sleep have been tightly linked to processes of cortical maturation (Buchmann et al., 2011) and a greater synaptic strength of neurons involved in the generation of slow wave oscillations (Kurth et al., 2010). Less is known about developmental changes in sleep spindle activity, but there is evidence that the number and density of spindles also declines from adolescence to adulthood (Nicolas, Petit, Rompré, & Montplasir, 2001), and some indication of an increasing trend during the first decade of life (Kurth et al., 2010).

Whilst ongoing neural development throughout childhood and adolescence has often been linked to increased sensitivity for learning (Knudsen, 2004), we now turn to consider the potentially important implications of these changes in the context of the CLS account, and review the behavioural studies that make direct developmental comparisons in consolidation processes.

3.1. Implications of brain development for consolidation processes

To understand the implications of brain development in consolidation processes, we must acknowledge changes that are happening in the two proposed memory systems across childhood and adolescence. First, we consider the development of the hippocampal memory system. Regions of the hippocampus are not fully matured in infants, but robust effects of sleep-associated consolidation are observed from approximately age 2.5 years (see Gómez & Edgin, 2015, for a review). In preschool children, the correlation between hippocampal volume and expressive language ability increases with age (Lee et al., 2015), suggesting that the maturing hippocampus may be a constraint on word learning in early infancy.

Later in childhood, it is less clear how ongoing subcortical maturation may impact learning and consolidation processes. Hippocampal mechanisms are thought to be in place by the time children reach school age (e.g., Gilmore et al., 2012; Seress, 2001), and longitudinal studies have not been able to pinpoint significant age-related changes in overall hippocampal volume during subsequent years (Giedd et al., 1996; Østby, Tamnes, Fjell, & Walhovd, 2011; Østby et al., 2009). However, there is some evidence of continued development throughout middle childhood and adolescence (Ghetti & Bunge, 2012), predominantly in a shift in relative mass towards posterior hippocampal regions (Gogtay et al., 2006). This corresponds to functional shifts apparent in both encoding (Ghetti, DeMaster, Yonelinas, & Bunge, 2010) and episodic retrieval tasks (DeMaster & Ghetti, 2013), during which adolescents and adults come to recruit more anterior regions of the hippocampus than children. Interestingly, a recent study suggests that the refinement of this anterior region is correlated with an increased ability to draw inferences across learning episodes (Schlichting, Guarino, Schapiro, Turk-Browne, & Preston, 2016). This ongoing development may therefore have important implications for learning strategies, and thus for teaching practices with different age groups.

Structural and functional differences in the hippocampus between children and adults *could* account for children's need for more sleep throughout development. For example, an immature hippocampus may be able to retain less information before requiring sleep, or may store weaker representations that require strengthening and linking to existing knowledge via sleep-associated processes. However, the implications of hippocampal changes for longer-term consolidation and sleep are supported by only tentative evidence. Østby et al. (2011) related the structural brain maturation of 8-19-year-olds to their immediate and delayed performance in a visuospatial memory task, and showed that hippocampal volume was predictive of memory performance one week later (but not of immediate performance). Furthermore, measures of structural hippocampal volume in children have shown positive correlations with weekday sleep duration (Taki et al., 2012), although the causal direction is unclear. These studies enable us to speculate that differences in hippocampal development could be impacting the relationship between learning and sleep in childhood. Nevertheless, there is a clear need for direct assessments between sleep, memory and hippocampal function in this age group, and it is important to acknowledge that learning itself will impact neural development (Blakemore & Bunge, 2012).

There is much clearer evidence for the protracted development of cortical regions throughout childhood and their associations with sleep. It has often been noted that the decrease in SWS during adolescence parallels continued changes in cortical grey matter at this age (e.g., Feinberg & Campbell, 2010). Buchmann et al. (2011) used structural magnetic resonance imaging (MRI) and overnight polysomnography measures to confirm a positive correlation between SWA and cortical grey matter throughout adolescence, with both factors decreasing with age. Regional analyses strengthened this link further: once controlling for overall decreases in SWA, the strongest decrease in SWA was observed in parietal regions that were undergoing the strongest decrease in grey matter volume, whereas relative increases in SWA were shown in regions of the prefrontal cortex still undergoing grey matter development. Slow-wave activity thus appears to be tightly linked to the developing brain, and could play a supporting role in the cortical reorganisation that occurs during this period of enhanced learning.

One study has spoken to the developing brain's capacity for sleep-associated neural reorganisation by combining neuroscientific measures with behavioural tasks. Wilhelm et al. (2014) found larger region-specific boosts in children's SWA after participants completed a visuomotor adaptation task, compared to adolescents and adults. Consistent with the findings above, baseline levels of SWA positively correlated with parietal grey matter volume. More interestingly, grey matter volume was also associated with the local increase in SWA following the adaption task, suggesting these developmental changes in SWA are linked to experience-dependent plasticity particularly in the maturing brain. Unfortunately, there was no follow-up task in this study to assess the behavioural implications of these enhanced sleep processes. Nevertheless, the study provides an insight into how sleep could play a key role in shaping cortical maturation processes across development.

3.2. Direct comparisons of consolidation effects between childhood and adulthood

The greater amounts of SWS seen in childhood and its connections to plasticity raise the possibility of superior consolidation processes: if SWS facilitates reactivation of hippocampal traces for stabilisation in the neocortex, then this should enable faster and/or larger consolidation effects in children. However, few studies have made direct comparisons between children and adults, particularly within the contexts of explicit and/or linguistic memory tasks relevant to word learning, and extant findings are mixed. Making such comparisons brings challenges to interpretation, as differences in the amount of information encoded could drive apparent differences in subsequent consolidation processes. From this perspective, it would be important to match groups in their baseline performance at encoding. However, matching the amount of information encoded could also lead to disparities in task difficulty for the groups of participants, suggesting that multi-faceted approaches will be important to address these questions.

Some of the most convincing evidence for enhanced sleep-associated processes in children has come from a study by Wilhelm et al. (2013), who looked at the extraction of explicit knowledge from an implicit motor sequence learned prior to sleep. Children aged 8-11 years and adults were given equal amounts of training on a motor task that required them to respond as quickly as possible to a sequence of light-up buttons on a response box, forming an implicitly learned motor sequence. After sleep, children were significantly better at explicitly recalling the next light buttons in the learned sequence, suggesting an enhanced ability to extract explicit knowledge from an implicit task, and performance was tightly correlated with levels of SWA on the night between training and test in both groups. In fact, children were so much better at this task than adults that the study was repeated in children with a more complex sequence, in order to better analyse the relationship with SWA in this population. The findings supported the proposal that, at least under certain conditions, greater amounts of SWA in children can support the high demands on learning that is characteristic of this stage of development.

Returning to the consideration of consolidation effects in language learning, a recent study by Weighall, Henderson, Barr, Cairney, and Gaskell (2016) also demonstrated a larger overnight benefit for children compared to adults in the explicit recall of newly learned words. In this study, 7-to-9-year-old children and adults both learned a total of 48 novel word-object pairings. Crucially, half of these pairings had been trained the day before – allowing for a night of sleep before testing – whereas the other half were learned on the same day as the test session. When given the task of completing the novel word forms from their stems (e.g., "which novel word began with *dol*?"), children showed a large advantage (36%) for words that had the opportunity for consolidation, whereas for adults this figure was significantly smaller (24%). In addition, a visual world eye-tracking paradigm was used to examined fixations to novel competitor objects (e.g., *dolpheg*) when asked to click on one of four pictures arranged in quadrants (e.g. "click on the *dolphin"*). Whilst both children and adults showed increased fixations to novel competitor objects (e.g., *dolpheg*), only children showed an enhanced overnight benefit of sleep (i.e., significantly greater competitor effects for consolidated than unconsolidated items). Although sleep recordings were not taken from children in this study, the behavioural evidence again supports that the characteristics of sleep during childhood could support rapid learning (and sleep spindles were clearly implicated for adults).

However, the differences in overnight sleep benefits for adults and children are not always evident: several studies have demonstrated comparable (Henderson et al., 2013b; Wilhelm, Diekelmann, & Born, 2008) or occasionally even larger (Henderson et al., 2015) overnight boosts in novel word recall performance for adults compared to children. For example, Wilhelm et al. (2008) had 6- to 8-year-old children and adults learn both verbal (semantically associated word pairs) and nonverbal (location pair) declarative stimuli. Sleep recordings showed that children had over double the amount of SWS than adults in the night between learning and test, yet children showed a comparable behavioural benefit to adult participants. These mixed findings highlight that the mechanisms and influences of learning may not be the same for adults and children, and point towards the need for more direct comparisons between adults and children to systematically address this question.

4. A role for existing knowledge

One proposal put forward by Wilhelm and colleagues (Groch et al., 2016; Wilhelm et al., 2008; 2012) is that adults have greater amounts of existing knowledge to support the fast consolidation of new information. Thus, children benefit from greater amounts of SWS, but adults can often compensate for their decreased amounts of SWS because of the higher levels of existing knowledge available to support integration. This proposal is in line with theories that suggest information is more readily integrated when consistent with existing schemata (Tse et al., 2007). Indeed, the most recent account of the CLS model emphasises that neocortical learning is not slower *per se*, but prior knowledge-dependent: new information that is consistent with existing knowledge produces little interference, and thus does not require the same extent of reactivation for cortical learning (McClelland, 2013).

Lewis and Durrant (2011) considered sleep-dependent mechanisms of integration in their *information overlap to abstract* (iOtA) model. They proposed that a new memory representation can activate relevant parts of schematic knowledge during encoding. During subsequent sleep, hippocampal reactivation of the representation amplifies the response of these overlapping neocortical neurons, thereby facilitating the integration of the new information with schematic knowledge via Hebbian learning principles. The greater the overlap between new and existing information, the more efficiently the integration can proceed as fewer new neural connections are required. From a developmental perspective, this would suggest that consolidation can proceed more rapidly in adults due to superior levels of existing knowledge, with reduced demands on processes during sleep, providing that the new information in question can capitalise on this.

The prior knowledge account could partially explain the mixed findings in studies that have compared the consolidation processes of adults and children. For example, in the study by Wilhelm et al. (2008), adults' greater amount of prior knowledge available to support the consolidation of word pairs could account for their similar overnight benefits to children, who instead showed greater amounts of SWS. Despite attempts to make their stimuli of equivalent difficulty across the two age groups, the extent of related or supporting prior knowledge that may be activated during learning is practically impossible to control. Further, the protracted development of anterior hippocampal regions across middle childhood may mean that the activation and integration of any prior knowledge is less consistent in this age group (Schlichting et al., 2016; see Section 3.1). Importantly, when existing semantic knowledge could not be capitalised upon in a motor sequence task, children showed enhanced sleep-associated benefits in comparison to adults (Wilhelm et al., 2013).

Such an explanation is supported by recent data from van Kesteren, Rijpkema, Ruiter, and Fernández (2013), which highlighted that individual items are particularly susceptible to the influence of prior knowledge on consolidation processes, compared to associations between them. Participants learned visual motifs paired with related or unrelated tactile fabrics, and were tested for both visual item recognition and the paired associates at different time intervals. Recognition of the items themselves was boosted for groups that had a 20- or 48-hour delay before testing to allow for consolidation processes to take place, whereas prior knowledge of associations (congruent visuo-tactile pairings) could benefit learning immediately. As a result, the consolidation benefit for schematic knowledge on associations was not as prominent. This earlier influence of schematic knowledge can also help to account for adults' generally higher level of performance but often smaller overnight consolidation effects relative to children: whilst adults experience greater benefit from existing knowledge during learning and/or consolidation, children benefit from enhanced SWS that facilitates overnight consolidation processes.

4.1. Existing vocabulary knowledge in word learning

In learning a new spoken word, we can consider the benefit of existing knowledge on both phonological and semantic aspects. If a word shares a similar phonological structure to existing words, then it can benefit from existing phonemic contingencies. Likewise, if the new word relates to known semantic concepts, then it can capitalise on knowledge about those concepts and thus require fewer new neural connections to be made. In comparing adults with children in language learning studies, we see a similar pattern to that described above: when adults could link novel words to prior knowledge in a story learning context, they showed better overnight improvements in cued recall of the words (Henderson et al., 2015), whereas children show the biggest improvements when words are linked to entirely novel objects (Weighall et al., 2016).

Within studies of developmental language acquisition, an influence of existing vocabulary knowledge predicts that children with superior vocabulary should demonstrate more efficient consolidation of new words. In this instance, a child can benefit from both enhanced SWS and good levels of prior knowledge. Henderson et al. (2015) explored this possibility further in their study of word learning (see also Horváth et al., 2015b, for similar findings in infants). In children aged 7-10 years, expressive vocabulary scores were positively correlated with overnight changes in both cued recall of newly learned words and lexical competition effects (the extent to which they became integrated with and influenced the processing of existing lexical neighbours). Also consistent with a delayed benefit of existing knowledge, Wilkinson and Houston-Price (2013) demonstrated that existing vocabulary knowledge accounted for over 20 per cent of variance in novel word memory 24 hours after training and after a further two weeks. However, a lack of an immediate test means it is not possible to pinpoint initial learning and consolidation processes in this latter study.

If existing vocabulary knowledge facilitates the processes of learning a new word, then this account is highly relevant for Matthew effects in word learning. In light of this proposal, we have conducted a meta-analysis of our existing novel word learning data from five previous studies that analysed the predictive relationship between existing vocabulary knowledge and overnight changes in phonological integration (Box 1). Standardised vocabulary scores were a unique predictor of lexical competition effects the next day (accounting for 10% of variance) after controlling for age, explicit retrieval of the word forms, and reaction times to control words. This relationship held regardless of whether the study included semantic elements of word learning; although the association was numerically stronger (albeit not significantly) when words had been trained in the context of meaning. Although we cannot conclude a causal direction for this relationship, and there are likely to be additional factors at play, the findings are consistent with a facilitatory effect of prior vocabulary knowledge in lexical consolidation, and we propose a number of studies to address this hypothesis in Section 5.

Furthermore, new words have also been demonstrated to integrate more quickly with existing vocabulary knowledge when both the novel word and existing neighbours are co-activated during learning. As previously mentioned, the neocortical system is proposed to be slower or *prior knowledge-dependent*, such that substantial links between existing knowledge and new information can lead to more rapid consolidation, without the need for sleep. For example, in contrast to studies that use the pause detection paradigm, new words tend to show immediate competition effects if they are learned using a "referent selection" procedure (Coutanche & Thompson-Schill, 2014). In these studies, participants identify the referent of a novel word by eliminating the known objects present, such that accessing prior knowledge during word learning appears to fast-track the consolidation of novel words. Further, words learned via referent selection do not further benefit from sleep processes (Himmer, Müller, Gais, & Schönauer, 2017). Whether children could also experience this immediate benefit in word learning via this procedure remains an important open question, with potential practical implications for vocabulary teaching methods.

[BOX 1 APPROXIMATELY HERE]

4.2. Experimental evidence for the role of existing vocabulary knowledge

The consolidation literature points to an additional means by which existing vocabulary can facilitate the acquisition of new words, and thus could partially account for Matthew effects found in development alongside enhanced exposure to novel vocabulary (Cain & Oakhill, 2011). It remains highly likely that the environmental factors of experience and exposure play key roles in helping the 'rich' get 'richer', but the contribution of prior knowledge to lexical consolidation suggests that the underlying neural mechanisms might also facilitate this effect.

Although this view of consolidation is a novel proposal for explaining vocabulary development of school-aged children, the facilitatory effect of existing knowledge on word learning gains support from areas of infant language acquisition. Computational analyses of early acquired semantic networks have led to the proposal of a preferential attachment theory, whereby highly connected words or concepts are more likely to acquire new connections (Hills, Maouene, Maouene, Sheya, & Smith, 2009; Steyvers & Tenenbaum, 2005). Borovsky, Ellis, Evans, and Elman (2015) built on this idea to propose a lexical leverage hypothesis in infant word learning: a given word should be more easily learned if it is entering a densely occupied semantic space, as a child can use their existing knowledge to make inferences about the new concept rather than build a new representation from scratch. Consistent with this hypothesis, they showed that an infant's existing knowledge of a semantic category (e.g., animals, clothes, fruit) was predictive of which words were learned more easily when taught new words from the same categories.

Perry, Axelsson, and Horst (2015) further demonstrated that the structure of an infant's existing vocabulary knowledge guides them towards *what* they learn about a new object. In this study, toddlers remembered more features about new objects if their vocabulary included more shape-based nouns, suggesting that their previous experiences helped to guide them towards what to learn about new concepts in order to successfully distinguish between them. These studies support the proposal that prior knowledge can indeed influence word learning in young children, and that this is a plausible factor in word learning throughout subsequent development.

5. The rich get richer: future directions

The evidence points towards an additional means by which children with good vocabulary knowledge could advance at a faster rate than those with poorer vocabulary. The consolidation account provides a testable explanation as to how Matthew effects might arise, suggesting that such effects could be a product of internal learning mechanisms as well as the environmental factors typically considered in previous research. Our meta-analysis supports a link between existing vocabulary knowledge and word learning ability, but it has yet to be tested experimentally in school-aged children to establish a causal influence. Here we propose some future directions for exploring this hypothesis further, and argue that consolidation effects should be considered as a factor in any complete account of vocabulary acquisition.

5.1. Developmental comparisons

First, there is a clear need for more direct and careful comparisons of sleep-associated consolidation effects across development. A key proposal made here and previously by others (e.g., Wilhelm et al., 2012) is that children are equipped for faster and superior consolidation effects due to enhanced levels of SWS and accompanying capacity for cortical reorganisation. Later in development, adults are advantaged by greater amounts of pre-existing knowledge that can in some instances bolster the integration of new information. Varied approaches are required to thoroughly test whether these different mechanisms are responsible for similar behavioural findings. In word learning, we might expect adults to always be able to gain from their superior language knowledge where words share phonological, orthographic or semantic neighbours, whereas overnight consolidation benefits would be stronger for children where new words and concepts share few similarities with existing knowledge.

As highlighted earlier, it will be important to draw behavioural comparisons when similar quantities of information are presented for learning (leaving variable prior knowledge contributions across participants), as well as when the to-be-learned information is manipulated to ensure equivalent levels of difficulty across younger and older participants. A comprehensive approach in language learning would thus be to compare consolidation effects in developmental groups when the groups are trained to criterion (e.g., successful performance on a given number of words) to when groups receive the same amount of exposures to the new words. An alternative approach would also be to include pre-training on novel material to create equivalent levels of prior knowledge across groups and observe subsequent consolidation effects of experimental items trained into them. Together, these comparisons would help to better specify the relationship between the demands of learning and subsequent sleep parameters, and their combined influence on overnight consolidation. Worthy comparisons could also be made regarding *when* existing knowledge plays a role on different aspects of language learning. Given evidence to suggest that prior knowledge contributes to a larger overnight consolidation effect for individual items compared to associations (van Kesteren et al., 2013), one might suggest that developmental differences in consolidation effects will be larger in word form recall than in associating new words with meanings. Furthermore, adults may show larger differences in overnight consolidation effects between items and associations than children, given the weaker influence of existing knowledge in the latter age group. The engagement of these different processes over the course of learning and consolidation could be further elucidated by using functional magnetic resonance imaging (fMRI) to compare the engaged neural mechanisms between adults and children.

Rather than manipulating the influence of prior knowledge in these studies, an alternative approach could focus on comparing the performance of adults and children following manipulation during sleep. A number of methods can be used to influence and enhance SWS architecture in adults, with consequences for memory performance: transcranial direct current stimulation has been used to successfully boost slow oscillation activity (Marshall et al., 2006), and auditory stimulation delivered in phase with slow oscillation up-states enhances subsequent slow oscillation activity and phase-locked spindle activity (Ngo, Martinetz, Born, & Mölle, 2013; Ngo et al., 2015). Thus, in word-learning designs that have minimised the influence of prior knowledge, it may be possible to bring the superior sleep-associated memory benefits of children to adults by enhancing their sleep architecture in this way. This would provide further support of the two contributing mechanisms to consolidation across development.

5.2. Manipulating the connections of new words to existing vocabulary knowledge

We can look for clearer evidence regarding the impact of existing knowledge on new word learning by manipulating the extent to which new information can capitalise on prior knowledge. If our findings of a relationship between existing vocabulary knowledge and overnight gains in word learning and lexical competition are due to the ease at which the new words can be integrated, then children with better vocabulary should show an advantage when learning words that are richly linked to their body of existing knowledge, compared to words that are less well linked to existing knowledge. However, if the source of individual differences lies elsewhere – for example, as a consequence of more general differences in the learning mechanisms or other variables that were not included in the present analyses (e.g., IQ, differences in sleep architecture) – then children with superior vocabulary should continue to show better gains regardless of the words they are learning.

We propose three ways by which connections with existing knowledge could be manipulated in word learning studies. First, as in the infant language studies described above, vocabulary across different semantic categories could be used categorise novel items as having weak or strong links to existing knowledge on an individual basis (Borovsky et al., 2015). For example, a child whose hobbies are primarily musical might show greater overnight benefits for instrument names compared to sport terminology, whereas a child who spends their weekends playing football might show the opposite effect.

Second – and perhaps most feasibly in school-aged children – novel items can be created that link to low or high density phonological, orthographic and/or semantic neighbourhoods. This manipulation makes broader predictions about the ease at which certain items should be integrated, and has already been used in one study of new semantic knowledge in adults (Tamminen et al., 2013). If sensitive enough to changing neighbourhoods across development, this may interact further with individual differences in vocabulary knowledge and provide an even stronger assessment of existing knowledge on word learning ability (see Storkel & Hoover, 2011, for a similar approach to immediate word learning in infants).

Third, more carefully controlled studies can manipulate the existing knowledge itself, such that later trained novel items can feature strong or weak links to existing knowledge. Although time intensive, similar approaches have been highly successful in unpicking the ease of assimilation effects in other areas of memory research (Hennies, Ralph, Kempkes, Cousins, & Lewis, 2016; Sommer, 2016). For example, Hennies et al. (2016) first taught participants a new schema over the course of two weeks. Participants were then presented with a series of facts to learn that were either consistent with their new knowledge or completely unrelated. Spindle density during the following night's sleep was predictive of a memory benefit for the related facts only, and predicted a decreased involvement of the hippocampus as shown by functional MRI scans the following day. A similar approach could therefore be taken to word learning, by creating sparse and high density phonological, orthographic and/or semantic neighbourhoods prior to training experimental items for analysis of consolidation effects.

5.3. Studies of atypical development

Another potentially informative approach will be to explore the learning and consolidation of new words in children with developmental disorders, especially considering the prevalence of sleep difficulties within these populations (e.g., Malow et al., 2006; Sadeh, Pergamin, & Bar-Haim, 2006). Sleep-associated consolidation differences have already been a topic of interest in children with developmental disorders, including children with autism (Henderson et al., 2014; Maski et al., 2015), ADHD (Prehn-Kristensen et al., 2011), and Williams Syndrome (Dimitriou, Karmiloff-Smith, Ashworth, & Hill, 2013). Here, it is important to consider the role of prior knowledge as well as sleep difficulties in order to better understand how to remediate and support learning in these groups. Again, multiple comparisons that match relative difficulty and the amount of knowledge learned across groups will be important to consider.

One group of particular interest in studying the influence of prior knowledge on vocabulary acquisition processes will be poor comprehenders: children who struggle to understand and make inferences from text or discourse, despite otherwise adequate phonological skills that support accurate word identification (Nation & Snowling, 1998; Stothard & Hulme, 1995). Such specific comprehension problems are apparent in approximately 5-10 per cent of school-aged children and constitute the largest proportion of reading deficits that emerge in later schooling (Catts, Compton, Tomblin, & Bridges, 2012). Research has shown that these children exhibit vocabulary deficits that are largely linked to the semantic component of word learning (Nation, Snowling, & Clarke, 2007). These vocabulary deficits clearly worsen over time (Cain & Oakhill, 2011), highlighting the importance of understanding word learning difficulties in these children at an early age.

Studies of word learning in poor comprehenders have demonstrated that these children show equivalent learning to typically developing children initially, but do not retain their new lexical knowledge well over time (Nation et al., 2007; Ricketts, Bishop, & Nation, 2008). Considered differently, poor comprehenders have the skills to learn new words – even when it places demands on their comprehension skills to infer their meanings from text (Ricketts et al., 2008) – but their impairment arises at the consolidation stage of learning. An fMRI study by Cutting et al. (2013) further reported increased hippocampal and parahippocampal involvement in word reading in children with specific reading comprehension difficulties, suggesting anomalies in connections between basic language-related areas (e.g., BA 44) and declarative memory systems. Given the role of hippocampal and parahippocampal regions in the initial encoding of episodic and semantic memories (Moscovitch et al., 2005), the authors speculated that poor comprehenders may have difficulty with cortical consolidation, or rely on hippocampal connections as a compensatory mechanism. A prime question here will therefore be whether poor comprehenders can be characterised as having a problem localised to the specific processes of consolidation, or whether these deficits are accounted for by their pre-existing deficits in vocabulary knowledge that provide weakened support for consolidation and integration of new words into long-term memory.

6. Conclusions

Sleep plays an important role in the stabilisation of newly learned memories and their integration with existing knowledge. Numerous studies have demonstrated this sleep-associated benefit in word learning, and have accumulated support for the specific roles of SWA and sleep spindles. We have reviewed evidence that suggests enhanced levels of SWS during childhood may support the greater amounts of learning experience at this time, enabling neural reorganisation as cortical networks continue to develop into adolescence. Consistent with Wilhelm and colleagues' proposal, we have suggested that links to prior knowledge can also facilitate consolidation during word learning, and the reviewed evidence of adults and children supports this suggestion. Furthermore, a meta-analysis of our previously published data has shown that individual differences in vocabulary knowledge are predictive of overnight consolidation effects during word learning. This provides a novel and robust demonstration of the Matthew Effect within the context of lexical consolidation.

The influence of existing vocabulary in supporting word learning has important implications for studying the trajectory of vocabulary development, and particularly in considering the means by which the 'rich get richer'. The reviewed studies suggest that neurological mechanisms could contribute to such Matthew effects in vocabulary, alongside differences in environment and exposure. Accounting for both types of influence is important in developing a complete model of word learning, and understanding how best to prevent children with poor vocabulary falling further behind.

However, there is a clear need for more direct and experimental approaches to this question, and we have provided a number of suggestions for future research in both typical and atypically developing populations. It is hoped that these will help to further our understanding of the mechanisms at play during word learning, and unpick the directional relationships between new information, existing knowledge, sleep processes and neural reorganisation.

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Box 1. Vocabulary ability as a unique predictor of overnight integration effects

Studies with school-aged children have shown that sleep works to integrate new phonological forms with existing lexical knowledge (Henderson, Devine, Weighall, & Gaskell, 2015; Henderson, Powell, Gaskell, & Norbury, 2014; Henderson, Weighall, Brown, & Gaskell, 2013a; Henderson, Weighall, & Gaskell, 2013b; Henderson, Weighall, Brown, & Gaskell, 2012). Such conclusions are based on the assumption that once a novel word has been integrated into long-term language networks, it should compete for recognition with known words. Studies have captured this 'lexical competition' effect with the pause detection task (Mattys & Clark, 2002). In this task, participants make speeded judgements on whether a 200ms pause is present or absent in a set of basewords (e.g., "dolph_in" or "dolphin", respectively) for which a new competitor has been taught (e.g., "dolpheg") and a set of control words for which no new competitors have been taught. Lexical competition (i.e., significantly slower responses to basewords than control words) seems to emerge after a consolidation period that includes sleep. This is the case when children are taught only the phonological forms of words via explicit instruction (Henderson et al., 2014; Henderson et al., 2013a; Henderson et al., 2012), when they are taught real words with meaning (Henderson et al., 2013b), and when they learn novel words via more implicit encounters in stories (Henderson et al., 2015). The latter study reported that children with better existing vocabulary knowledge show larger overnight gains in lexical competition. This provides some evidence that existing vocabulary knowledge might work to bolster the consolidation of new language, that superior consolidation processes facilitate the growth of vocabulary, or both. However, it remains possible that the correlation between existing vocabulary and overnight consolidation of new vocabulary occurred as a consequence of teaching novel words in stories. Namely, children with richer vocabulary knowledge may be better at comprehending the story, leaving more resources available for novel word learning and/or consolidation.

To address this issue, we combined data from five of our previous studies, three of which trained novel phonological forms (e.g., dolpheg) via phonological training tasks (e.g., repetition, initial and final phoneme segmentation, phoneme monitoring) without including any reference to novel word meaning (Henderson et al., 2012; Henderson et al., 2014; Henderson et al., 2013a), and two of which taught novel words with meanings (i.e., real words with definitions, Henderson et al., 2013b; novel words in spoken stories, Henderson et al., 2015). A total of 158 children participated in these studies: 90 in the 'no meaning' studies (mean age 9.61 years, SD=1.69, range 7-13 years) and 68 in the 'meaning' studies (mean age 8.38 years, SD=1.18, 6-10 years). It should be noted that in Henderson et al (2014) only the typically developing children (and not the children with diagnoses of autism spectrum disorder) were included in the present analyses, but all other child participants were included.

Given that the magnitude of overnight change can depend on baseline performance, hierarchical regression analyses were conducted predicting Day 2 lexical competition while controlling for Day 1 lexical competition, Day 1 pause detection RT for the control condition, and Day 1 cued recall performance, with standardised vocabulary scores as the key predictor. Vocabulary was measured via the Peabody Picture Vocabulary Test in all studies except Henderson et al. (2015), which used the Vocabulary subtest from the Weschsler Abbreviated Test of Intelligence. As shown in Table 1, vocabulary knowledge accounts for significant variance in lexical competition effects on the day after training when pooling data across all studies (Model 1), and when word learning occurs with meaning (Model 2) or without meaning (Model 3). The unstandardized regression coefficients for Models 2 and 3 did not significantly differ (Fischer's r-z transformed z score = .50), confirming that vocabulary was a significant predictor of lexical competition on Day 2, regardless of whether words were taught in the context of their meanings or not. Partial correlations, controlling for age and Day 1 lexical competition effects further demonstrate that children with better existing vocabulary knowledge showed larger overnight gains in lexical competition from Day 1 to Day 2 ($r(154)=.27$, $p<.001$). Although vocabulary appeared to account for twice as much variance in studies that provided meanings versus no meanings, these correlations did not significantly differ in magnitude ('no meaning' studies: $r(86)=.22$, $p<.05$; 'meaning' studies: $r(64)=.35$, $p<.01$) (Fischer's r-z transformed z score = -.86) (see Figure 1).

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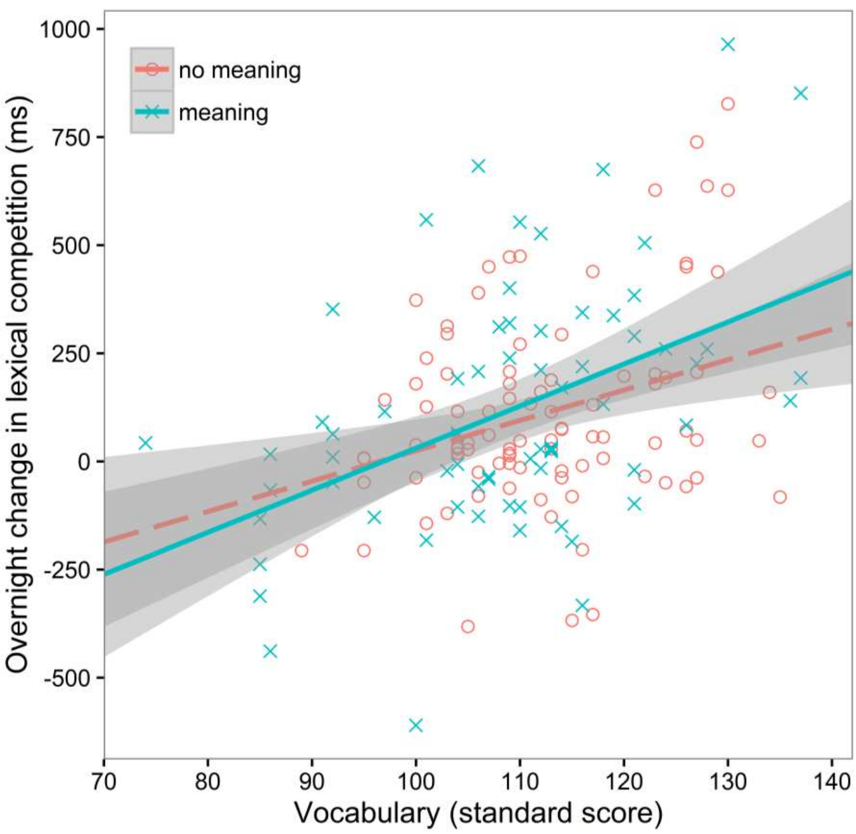

Figure 1. A scatterplot showing the positive correlation between overnight changes in lexical competition from Day 1 to Day 2 (=(Competitor RT – Control RT Day 2) – (Competitor RT – Control RT Day 1)) and standardised vocabulary scores (mean for age = 100, SD = 15), for the 'meaning' and 'no meaning' studies separately. Grey bands represent 95% confidence intervals.

Table 1. Hierarchical regression analyses predicting Day 2 lexical competition (Competitor pause detection RT – Control pause detection RT) from standardised vocabulary scores, when controlling for Day 1 lexical competition, Day 1 Control pause detection RT, and Day 1 cued recall performance. Results are presented separately for a combined analysis across all studies, and for the 'meaning' and 'no meaning' studies. *Note* * *p* < .05, ** *p* < .01, *** *p* < .001

Model	**Step**	**Predictors**	**R^2**	**ΔR^2**	**F change**	**β**
1 - All studies	1	Lexical competition Day 1	.02	.02	1.07	.04
(n = 158)		Control RT Day 1				.02
		Cued Recall Day 1				.16
	2	Vocabulary	.11	.09	14.46***	.31***
2 - Meaning studies	1	Lexical competition Day 1	.08	.08	1.79	.03
(n = 68)		Control RT Day 1				-.19
		Cued Recall Day 1				.24
	2	Vocabulary	.19	.12	9.14**	.36**
No Meaning studies	1	Lexical competition Day 1	0.2	.02	0.48	.05
(n = 90)		Control RT Day 1				.10
		Cued Recall Day 1				.18
	2	Vocabulary	.07	.05	4.97*	.24*