Developmental and Individual Differences in the Timecourse of Prior Knowledge and Offline Consolidation Support in the Vocabulary Learning of Adults and Children

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Abstract

Vocabulary is a fundamental component in communication and literacy development. This thesis investigated when prior semantic knowledge and memory consolidation support vocabulary learning, characterising developmental and individual differences in these mechanisms. Existing research suggests children's word learning benefits more from memory consolidation, potentially underpinned by developmental differences in sleep architecture, whereas adults benefit from a mature language system and greater prior knowledge. The thesis addresses the possible sources of this developmental difference by comparing the learning trajectory of children aged 9 to 11 and adults across one week. To test the role of specific connections with prior knowledge, novel words were paired with pictures providing strong local connections with real animals or weak connections through fictitious creatures, and abstract patterns with no semantics. Across five experiments, word form recall was tested immediately and after a one-week delay, with an additional test after a 10-minute or 1-day delay. Semantic benefits enhanced adults' word recall, especially in tasks that demand form-meaning retrieval, from the immediate test and were maintained across delays; but children showed no prior knowledge benefit. Whereas children showed particular benefits from offline consolidation, during which their memory improved over tests spanning nocturnal sleep, but not over daytime rest. Adults showed a smaller consolidation effect, especially in the absence of reconsolidation opportunities from interleaved tests. Direct developmental comparisons demonstrated children's superior improvements across periods of offline consolidation. Global linguistics skills predicted the overall word recall across test points of children and in more diverse adult samples but did not influence the extent to which local semantic connections could be benefited. This thesis demonstrates developmental stability and changes in the mechanisms that underpin word learning: Children rely more on offline consolidation processes whilst adults benefit more from local semantic connections, but both can benefit from global linguistic skills.

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A song of Ascents. Of Solomon.

Unless the LORD builds the house,
those who build it labour in vain.
Unless the LORD watches over the city,
the watchman stays awake in vain.
It is in vain that you rise up early and go late to rest,
eating the bread of anxious toil;
for he gives to his beloved sleep.

Behold, children are a heritage from the LORD,
the fruit of the womb a reward.
Like arrows in the hand of a warrior
are the children of one's youth.
Blessed is the man
who fills his quiver with them!
He shall not be put to shame
when he speaks with his enemies in the gate.

Psalm 127

Author's Declaration

This thesis is a presentation of original work completed solely by the author, under the supervision of Dr Emma Hayiou-Thomas and Professor Lisa Henderson. This work has not previously been presented for a degree or other qualification at this University or elsewhere. All sources are acknowledged as references.

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Chapter 1 Introduction

Vocabulary knowledge plays an important role in supporting language proficiency and development. The acquisition of lexical knowledge is a life-long process: while infants and children can accumulate new words rapidly, substantial vocabulary growth continues into adulthood (Brysbaert et al., 2016). Vocabulary is essential for literacy acquisition (Duff et al., 2015) and reading comprehension (J. M. Quinn et al., 2015; Suggate et al., 2018), with lasting impact on later education attainment, employment and mental health (Armstrong et al., 2017; Spencer et al., 2017). Given the crucial role of vocabulary knowledge, studies have also shown that discrepancies in vocabulary across race and socioeconomic status persist across childhood (Farkas & Beron, 2004), with children from families of lower socioeconomic status showing smaller vocabulary gains from preschool and from language interventions (Becker, 2011; Marulis & Neuman, 2013). Importantly, vocabulary acquisition exhibits a "Matthew Effect" (Stanovich, 1986), such that children with stronger vocabulary abilities show more rapid vocabulary growth than their peers, hence "the rich get richer" (Cain & Oakhill, 2011). Understanding the mechanisms underlying word learning is therefore essential for developing effective support for all learners, particularly those who experience difficulties in language or literacy development.

Word learning has been studied and conceptualised through various theoretical lenses. The current work examines word learning as establishing new representations through memory processes (Jackson et al., 2021; Wojcik, 2013) that depend on sleep (Davis & Gaskell, 2009). Within this framework, consolidation mechanisms and prior knowledge are two important processes supporting word learning. Yet, few studies have systematically examined the timecourse of prior knowledge contributions to word learning and consolidation. This question is particularly important across development, as children and adults differ in the strength of their consolidation and the maturity of semantic knowledge (Hills et al., 2009; James et al., 2017; Peiffer et al., 2020; Wilhelm et al., 2012), which may influence when prior knowledge can support learning. This thesis aims to address these critical questions by examining the contribution of semantic prior knowledge and memory mechanisms to support the consolidation of newly learned words across one week.

The following sections review the literature on sleep-dependent consolidation and prior knowledge in novel word learning. We will consider both the semantic information presented during learning, which could form specific "local" associations with prior knowledge, and the prior knowledge provided by “global” linguistic skills - such as existing vocabulary knowledge - that individuals utilise during learning, and which varies across and within each developmental stage. Importantly, this review examines when in the timecourse of word learning semantics might exert its influence. While sleep plays an important role in novel word consolidation and integration, this review also includes emerging literature on the interaction between semantic support and sleep-dependent consolidation.

1.1 Offline memory consolidation support for word learning

Acquiring a new spoken word can be conceptualised as forming a new phonological representation that must be encoded and consolidated for later successful retrieval. Following encoding, consolidation processes stabilise and integrate the new word memories with existing knowledge, but different theoretical frameworks diverge in terms of the conditions considered to be beneficial to consolidation.

The Complementary Learning System (CLS) framework (McClelland et al., 1995)proposes that memory and knowledge acquisition rely on two memory systems. The need for two separate memory storage systems stems from the balance between quickly encoding new information without interfering with existing knowledge. The hippocampal learning system is characterised by sparser, non-overlapping storage that allows for rapid acquisition of new information without influencing existing knowledge. The neocortical learning system is a distributed network in which different knowledge and memories are presented through patterns of activation from a network of interconnecting and highly overlapping processing units. The CLS approach suggests that integration of new knowledge into the neocortical system is a slow and prolonged process that requires repeated reactivation to gradually transfer from the hippocampus to neocortical networks. One potential way for this shift in the dependence on the neocortical system to occur is through sleep, based on the active systems consolidation process (Born & Wilhelm, 2012; Davis & Gaskell, 2009; Diekelmann & Born, 2010). Alternatively, the opportunistic theories propose the importance of a period of reduced interference that is free from new encoding demands to stabilise previously encoded memories (Mednick et al., 2011); while further accounts focus on the role of repeated exposure and retrieval to aid memory consolidation (Antony et al., 2017).

In this section, we discuss the core concepts of sleep and memory consolidation, especially their benefits in word learning, before considering the consistency and differences of sleep consolidation effects from childhood to adulthood.

1.1.1 Theories of sleep and memory consolidation

Active system consolidation theory suggests that sleep processes play an active role in enhancing and strengthening memory traces, in addition to protecting memories from decaying. Across the two core stages of sleep – slow wave sleep (SWS) and rapid eye movement (REM) sleep, recent research has converged on actively reactivating and strengthening memories during SWS, which primarily occurs during sleep stage 3. Memory consolidation at these stages is characterised by the involvement of slow oscillation, spindles, and ripples, occurring concordantly to support hippocampal and neocortical information transfer (Diekelmann & Born, 2010; Gais & Born, 2004). Slow oscillations are high-amplitude slow waves (<1 Hz) of alternating hyperpolarised and depolarised states generated in the neocortical networks and propagate across the cortex (Kurth et al., 2017). In contrast, sleep spindles are marked by short burst activities at the 12-15 Hz band originating from the thalamus to correlate activation between the hippocampus and the frontal regions (Muehlroth et al., 2019). Ripples (80-140 Hz) are sharp waves originating in the hippocampal network, which signify memory replay and neuronal reactivation (Klinzing et al., 2019). These components, especially the coupling of slow oscillation and sleep spindles, reflect successful memory consolidation as enhanced coupling is related to better memory performance post-sleep (Bastian et al., 2022). Furthermore, these components also change across the development trajectory. Slow wave activities increase across childhood until late childhood, followed by a decrease during adolescence (Kurth et al., 2010). In a recent study, Joechner et al. (2023) examined age-specific patterns of sleep architecture across participants aged 5 to 26, demonstrating qualitative changes in slow oscillation-spindle coupling, as well as the maturity of individual components from childhood through to early adulthood. Given that memory consolidation depends critically on these sleep parameters, developmental changes in sleep architecture are expected to be reflected in consolidation differences across age (see Section 1.1.3).

The active system consolidation hypothesis suggests that newly encoded memories are actively reactivated and consolidated during SWS (Born & Wilhelm, 2012). Following the two-stage model of the CLS framework, newly encoded memories are selectively activated during SWS, which facilitates the transfer of memories from short-term hippocampal storage to long-term cortical areas through the sleep parameters discussed above. To connect behavioural performance with electrophysiological measurements of SWS components during sleep, Dehnavi et al. (2021) showed that slow oscillations and spindle nesting were correlated with the amount of retention and consolidation in declarative memory. Therefore, sleep actively supports declarative memory consolidation by facilitating the transfer and integration of new memories with the distributed network of existing knowledge in the neocortex.

Apart from actively supporting consolidation and reorganisation of memory, sleep is also responsible for restoring encoding capacities to enable subsequent learning. The synaptic homeostasis hypothesis (SHY) proposes that sleep helps to restore synaptic capacity for more learning during wakefulness (Tononi & Cirelli, 2014). The encoding of new information during wakefulness increases synaptic strength across the neural network. During SWS, synapses are descaled and their synaptic strength is reduced, as reflected in slow wave activity measurements measured by electroencephalogram (EEG), and restores learning capacity for the next day.

The relationship between sleep and learning is also bidirectional: in addition to sleep supporting memory consolidation, learning also modulates subsequent sleep parameter activities. A change in sleep spindle and slow wave activity has been found during the subsequent sleep following word learning, in which a greater increase in spindle activities was associated with learning words with potentially more interference from semantic neighbours (Tamminen et al., 2013). Furthermore, consolidation of motor sequences was also reflected in hemispheric-specific changes in spindle activity, suggesting that memory system activities could be adapted to reflect consolidation demands (Fogel & Smith, 2011; Nishida & Walker, 2007).

1.1.2 Sleep consolidation benefits for new words

When viewing word learning through the lens of theories and models of memory, learning a new word form shares similar processes to acquiring a new memory and going through processes of encoding, consolidation, and retrieval (McGregor et al., 2020). Adopting the CLS framework, Davis & Gaskell (2009) proposed a two-stage account to illustrate word learning: the hippocampus rapidly acquires novel word representations, followed by a slower process of integrating the novel word form with the existing lexical network. Therefore, a key prediction is that novel word representations would be consolidated and integrated into the existing lexical networks after sleep, compared to immediately after learning or following wakefulness.

Evidence for this prediction comes from studies of novel word learning, during which participants learned phonologically plausible nonwords either in isolation (e.g. Dumay & Gaskell, 2007; Tamminen et al., 2010) or paired with meaning provided through pictures (Landi et al., 2018; Takashima et al., 2014), definitions (Bakker et al., 2015; van der Ven et al., 2015) or in context (James et al., 2021). Successes in word learning are indicated through changes in explicit recall and recognition of the novel words or through lexical competition, which indicates integration into the lexicon. These measures are typically administered immediately after learning and after delays ranging from 12-hour periods (encompassing sleep or wake) to 24 hours or one week, with the same tests repeated across sessions to track consolidation. New words become fully lexicalised when they are embedded in the lexical network and start to engage with existing entries in the vocabulary (Leach & Samuel, 2007). This engagement can be demonstrated through increased competition with its neighbours – existing familiar words that are lexically similar to the new word – during word recognition.

Dumay & Gaskell (2007) provided evidence that sleep-dependent consolidation facilitates integration of new lexical entries. After learning a novel word (e.g. "cathedruke") that was phonologically similar to existing familiar words (e.g. "cathedral"), adults showed greater improvements in free recall and slower lexical decision for existing familiar words following overnight sleep. During post-sleep testing, increased recall accuracy and slower reaction time in a pause detection task indicated that novel words were co-activated and competing with existing words. In contrast, participants who learned the novel words in the morning showed no similar improvements and competition when they were tested 12 hours later in the absence of an interim sleep; these effects only emerged 24 hours after learning, when the delay included a period of sleep. This pattern of results provides support for adopting a CLS account to word learning processes, as integration was demonstrated through changes in memory and coarticulation from existing vocabulary after overnight consolidation.

Strengthening the link between neural activity during sleep and learning, Tamminen et al. (2010) showed the role of spindles in promoting the transfer from hippocampal representations to neocortical representations during post-learning overnight sleep. Polysomnography (PSG) results showed a correlation between lexical competition effects and spindle activity, such that greater lexical competition effects were associated with high spindle count. Behaviourally, a greater benefit for sleep than wake was demonstrated in the free recall and recognition of the newly learned words. Critically, improvements in these explicit tasks were only found after a period of sleep but not after an equivalent period of daytime wakefulness, showing that sleep is critical for strengthening explicit memories of new word forms, rather than a period of delay alone. In a recent meta-analysis reviewing the effect of sleep in word recall, recognition and lexical integration confirmed moderate effects of sleep in both word recall and recognition, with a small effect for lexical integration (Schimke et al., 2021), further demonstrating the role of sleep in supporting explicit memory of phonological forms.

The design of the training and testing regimes can influence the magnitude of sleep consolidation effects, such as the perceived importance and future relevance of the information (Wilhelm et al., 2011). Encoding strength, or level of learning, also impacts the need for consolidation. When encoding strength is weak, lexical competition effects were compromised following sleep, suggesting that sufficient encoding is required to initiate integration during offline consolidation (Walker et al., 2019). In contrast, free recall accuracy benefited from stronger encoding, along with long intervals between learning and sleep onset, providing preliminary evidence for wake-based consolidation processes. Nevertheless, other works diverge on changes to the magnitude of sleep consolidation under different levels of learning, with studies showing that sleep consolidation benefits are greater at lower levels of performance (Denis et al., 2020; Drosopoulos et al., 2007), whilst Talamini et al. (2008) suggested that strongly encoded face-location pairs could be better preserved during sleep.

Thus far, I have presented evidence for sleep benefiting word learning and consolidation. Yet, it is important to emphasise that it is not the only essential condition, as hinted in Walker et al. (2019). Some studies demonstrate that integration of new words into the mental lexicon can occur immediately after learning, demonstrating lexical competition effects under specific circumstances. For example, Lindsay and Gaskell (2013) showed that incorporating retrieval practice in a training paradigm that interleaved novel words with familiar phonological neighbours led to the lexical competition effect without a period of offline consolidation. Similarly, Antony et al. (2017) proposed that active retrieval practice provides opportunities for online reactivation, boosting the co-activation of the hippocampus and neocortex and enabling more rapid integration.

An alternative account proposes that consolidation benefits may occur during any period of reduced encoding demands, not exclusive to sleep. The opportunistic theory of memory consolidation (Mednick et al., 2011) proposes that when encoding demands are low, newly acquired memory representations can be stabilised - protecting the representations from interference - and integrated with existing. Following this view, other periods of reduced interference, when the hippocampus is not actively encoding new information, can use these available resources to support consolidation. Therefore, both SWS and other low-interference states, such as during quiet wakeful rest, should facilitate declarative memory consolidation. Evidence from a range of declarative tasks suggests that even a brief 10–30-minute wakeful rest period can benefit retention compared to the equivalent period filled with cognitively demanding tasks (Dewar et al., 2012; Tucker et al., 2020; Wamsley, 2022).

If consolidation depends primarily on reduced interference rather than sleep-specific processes, then equivalent durations of wakeful rest and sleep should produce comparable memory benefits. Heim et al. (2017) tested this by comparing changes in memories of picture-pseudoword pairs either a 90-minute nap, an equivalent period of wakeful rest or an interference period involving further learning. Memory improved following the nap condition but showed significant forgetting in the wakeful rest and interference conditions, suggesting that sleep provides additional benefits beyond wakeful rest. Nevertheless, wakeful rest was less detrimental than the interference condition, although differences in initial recognition performance prevented strong inferences. This pattern raises the question of whether wakeful rest provides some stabilisation of recently learned words, or whether sleep-specific mechanisms outlined in the previous section are necessary for robust lexical integration.

To summarise the role of sleep in adults' word learning, a period of post-learning sleep has been found to support the consolidation of novel word forms, resulting in improvements in recall performance. However, the magnitude of the sleep benefits appears to depend on several factors, including the level of encoding, the length of duration between learning and sleep, and the availability of retrieval practice opportunities. It is important to note that much of this adult research focuses on the consolidation and recall of phonological or orthographic word form information, rather than the learning of word meaning or the retention of form-meaning mapping. This is important to address, given that the purpose of language is to acquire and convey meaning.

1.1.3 Consolidation in children's word learning

The CLS framework has largely been developed based on adult and animal research, with relatively less input from studies of human children (Diekelmann et al., 2009). This is an important omission as developmental differences, such as changes in sleep architecture and the increase in hippocampal-neocortical connectivity strength with age, may influence consolidation processes. As described in Section 1.1, sleep architecture changes across lifespan, with children show a higher percentage of SWS than adults (Ohayon et al., 2004), while slow oscillation declines from its peak late childhood (Feinberg & Campbell, 2010; Joechner et al., 2023) and spindle density increasing from childhood until adolescence, before declining across adulthood (Purcell et al., 2017). Behaviourally, although adults benefited from sleep consolidation effects in the acquisition of both declarative and procedural memories (Diekelmann & Born, 2010), a similar effect was found in declarative memory tasks but more limited on procedural memory in children (Fischer et al., 2006; Wilhelm et al., 2008, 2012). Therefore, as memory consolidation depends on processes that are changing across the developmental trajectory, we might expect qualitative and quantitative differences in processes of consolidation due to differences in sleep architecture.

Consolidation and integration of novel word forms have been observed after sleep across development from infancy onwards. Early evidence from infants and toddlers demonstrates that post-learning naps benefit early word recognition and label generalisation (Friedrich et al., 2015; Horváth et al., 2015). This suggests that sleep-dependent memory benefits can be measured from as early as 3 months of age (Horváth et al., 2018; see Mason & Spencer, 2022, for a review).

In school-aged children, sleep consolidation benefits have been demonstrated through improvements in recall and recognition of novel words. Henderson et al. (2012) taught children aged 7 to 12 novel words that were phonologically similar to familiar words using a phoneme monitoring task, before testing children's explicit memory with phonological form cued recall and form recognition, as well as lexical integration using a pause detection test. These tests were administered immediately, after a 12-hour delay and after a 24-hour delay. Children who slept shortly after learning the novel words, within the first 12-hour window, demonstrated continuous improvements in phonological form cued recall following the first 12-hour delay, at 24-hour delay and after a 1-week delay. Lexical competition was also observed after sleep, indicating successful integration. In contrast, children who learned words in the morning showed no improvements in recall or lexical integration following the 12-hour delay spent in wakefulness. However, when tested after 24 hours, which included an overnight sleep consolidation opportunity, significant improvements in recall and a lexical competition effect were found. This pattern demonstrates that the strengthening of explicit memory and the integration of new phonological forms into the lexicon of children take place across a period that encompasses sleep. Similar patterns of sleep-dependent consolidation with comparable testing schedules have been replicated for learning novel word-picture pairs by Ashworth et al. (2014) and James et al. (2020), demonstrating the robustness of the sleep benefit across a varied sample and learning materials. This pattern also matches the findings of adults (Dumay & Gaskell, 2007), demonstrating that sleep processes are crucial to the consolidation of newly learned words throughout development.

The consolidation benefits of sleep extend beyond overnight sleep consolidation opportunities and can be seen in daytime naps in preschool and school-aged children, although the memory benefits tend to be smaller than those following overnight sleep, potentially due to shorter sleep duration (Lo et al., 2014). Using an object-location learning task, Kurdziel et al. (2013) showed that when preschool children napped, they showed better recall of these new spatial locations. In contrast, when children were kept awake during this interval, significant forgetting was found. Importantly, the recall performance of the nap group remained superior after the subsequent overnight sleep, suggesting that sleep consolidation soon after learning may support the stabilisation for long-term consolidation. During nap, sleep spindle density was correlated with both immediate test performance and proportional changes in memory; thus, it is hard to dissociate whether changes in recall and differences in sleep density were a consequence of learning performance or inherent consolidation capacity. As children's midday naps are mainly composed of SWS, with little to no REM sleep, these results have further demonstrated an active involvement of sleep components in memory consolidation. The benefits of post-learning naps also benefited other types of stimuli, including recognising novel word-object pairs acquired through fast mapping (Axelsson et al., 2018), novel objects and functions (Urbain et al., 2016)and recalling the sequence of a story (Lokhandwala & Spencer, 2021; although see H.-C. Wang et al., 2022, who showed naps supported letter-sound generalisation but not explicit recall).

In contrast to robust sleep and nap benefits, evidence for wakeful rest benefiting word consolidation in children is more limited. Martini et al. (2021) showed that word list recall was better preserved when children and adolescents aged 10-13 engaged in wakeful rest following encoding compared to watching movie clips. Similar retention benefits of rest were found even when children and adolescents were tested after a 7-day delay instead of within the same day (Martini et al., 2019), suggesting that wakeful rest can potentially support long-term sleep-based consolidation benefits by preserving the encoded traces. However, these studies examined the recall of familiar words rather than establishing new lexical representations as in word learning; therefore, it is unclear if the role of wakeful rest might differ with the increased consolidation demands.

1.1.4 Developmental differences in consolidation benefits for word learning

An accumulation of studies directly comparing the performance of adults and children suggests that the size of overnight consolidation effects is bigger in children (for a review, see James et al., 2017). Multiple factors may contribute to this developmental difference, including changes in sleep architecture across development. Children show higher slow-wave activation and longer slow-wave sleep duration than adults; thus, there could be an enhanced reactivation of hippocampal memory representations in children (see Section 1.1.3, James et al., 2017; Wilhelm et al., 2013). Greater overnight improvements in cued phonological form recall were found in children by Weighall et al. (2017). Novel word-object pairs were presented during training in which adult and child participants learned half of the set on the day before testing, and the other half immediately before a test. Both groups of participants demonstrated overnight improvements in the recall of words learned the previous day, with children showing greater overnight benefits than adults. Lexical competition was evaluated using a visual world eye-tracking paradigm, which examined fixation to target and competing objects. A greater overnight benefit for items learned in the previous day, compared with items learned immediately before testing, was demonstrated in children only.

Extending these findings, James et al. (2019) examined when adults and school-aged children learned novel words that varied in the number of lexical neighbours. Children relied more heavily on sleep consolidation processes, resulting in greater improvements across both a 1-day and 1-week delay than adults (James et al., 2019, 2023; Peiffer et al., 2020). The contribution of consolidation mechanisms was highlighted in contexts where adults cannot capitalise on their prior knowledge in a novel object learning task. Peiffer et al. (2020) introduced pictures of novel “non-objects” and their functional definitions to adults and children, and these object-definition pairs were trained to criterion. During the delayed retrieval test, child participants showed greater overnight gain than adults, demonstrating that children's memory consolidation benefits more through sleep processes in the absence of the involvement of prior knowledge.

Apart from developmental differences in overnight consolidation, children also show greater effects of napping on memory than adults. van Rijn et al. (2023) demonstrated that napping supported the retention of novel words in adults and children, relative to an equivalent period of wake, which led to forgetting. Participants learnt novel words through a phoneme monitoring and repetition task without semantic information, and their lexical integration, phonological form recall and recognition were tested before and after a 90-minute afternoon nap. For phonological form recall, napping was more beneficial to children than adults, as children showed a slight increase in recall accuracy while adults still showed some forgetting. While children's naps, similar to overnight sleep, contained a higher proportion of SWS sleep than adults, the time spent in SWS was not correlated with children's recall improvement, and there was no evidence for lexical integration. The authors thus suggested that enhanced passive protection may have supported consolidation during children's naps. This finding raises the question of whether developmental differences in consolidation observed across longer periods of delay may also partly reflect similar passive protective mechanisms, rather than being solely attributed to SWS.

1.2 The role of "local" prior knowledge

While children showed more SWS than adults supporting overnight consolidation, adults possess more extensive prior knowledge to support their learning and consolidation (James et al., 2019, 2017; Wilhelm et al., 2012). The question of "when" prior knowledge supports word learning can be understood in two ways: first, at what point of the word learning timecourse does prior knowledge exert its influence, specifically during encoding, consolidation, or both (the focus of Section 1.3); second, at what point in development can prior knowledge be used effectively? The current section focuses on "local" prior knowledge, especially the semantic information available during learning, such as pictures, definitions or contextual cues; it also examines the type of semantic relationships that are beneficial for establishing novel lexical representations, and whether these relationships are beneficial to children, adults or both.

1.2.1 Encoding benefits from the presence of semantic information

Semantic association is a particular type of prior knowledge worth special consideration as it promotes deeper information processing and leads to better retention (Craik & Lockhart, 1972). In contrast, shallower levels of processing, such as perceptual processing (e.g. rhyme recognition), produce weaker memory traces that are more prone to decay. Hence, encoding and consolidation conditions that encourage semantic processing should lead to better learning than perceptual-based learning conditions without semantic information.

The presence of semantic information in the learning context has been found to support short-term retention of novel word forms. The semantic binding hypothesis suggests that the presence of semantic information promotes the stability of phonological sequences in immediate serial recall tasks (ISR, Jefferies et al., 2006). Although this hypothesis was developed to explain semantic impairments in semantic dementia patients, studies with neurotypical adult participants showed that new unfamiliar nonwords and nonword sentences were recalled with higher accuracy when they were semantically meaningful (Savill et al., 2017, 2018). After repeated presentation, nonwords might start to lexicalise and embed in the lexical network. In a model connecting the mechanisms underlying ISR, repeated learning effects and phonological word form learning, Page and Norris (Hawkins et al., 2015; Henderson et al., 2013; Leach & Samuel, 2007; Takashima et al., 2014) proposed that elements that were repeatedly learned and recalled would lead to increasingly more specific patterns of activation and become easier to recognize.

The presence of semantic information can also promote the encoding of new word form representations. The dual coding theory (DCT, Paivio, 2014) suggests that the presence of a picture enhances memory of spoken words because humans possess two separate, but interconnecting systems dedicated to verbal linguistic and visual imagery information, respectively. Under the DCT, verbal and visual information together result in an additive effect on memory retrieval, such that more items of verbal information will be remembered when accompanied by visual stimuli. Therefore, presenting images along with novel words will increase recall compared to presenting the word forms alone. Evidence supporting the DCT has been found in novel word learning studies where participants learned new word forms either in the presence or absence of a visual referent (Hawkins et al., 2015; Henderson et al., 2013; Leach & Samuel, 2007; Takashima et al., 2014). In a series of experiments comparing the novel word learning under different learning conditions, Leach and Samuel (2007) showed that picture association yielded better lexical engagement than novel word learning from short prose or in isolation. Lexical engagement was measured through a phonetic retuning task, in which participants would shift their phonemic categorical boundaries after exposure to ambiguous phonemes within real words. Novel words trained alongside pictures of novel objects showed greater phonemic retuning effects than novel words embedded in short passages or in isolation, suggesting that novel words were better engaged at the phonemic level when explicit semantic information was provided during learning. Therefore, the presence of semantic information benefits the immediate recall of novel word forms. In particular, semantic information provided through illustrations and pictures is shown to be more beneficial to support the engagement of novel words with existing lexical knowledge.

1.2.2 Semantic benefits from connections with prior knowledge

Building on the benefits of the presence of semantic information, it is important to establish what type of semantic connections may support word learning effectively. Under the CLS framework, McClelland (2013) emphasised the importance of prior knowledge or schema-consistency. It is suggested that neocortical learning is prior knowledge-dependent, where consolidation can take place rapidly if a new word can create an association and be incorporated into the neocortical network directly, on the grounds that new schema-consistent information should not interfere and overwrite existing knowledge. Schemata support episodic information to be semanticised and organised as a network of associations, allowing it to be used flexibly (Tse et al., 2007, 2011). In contrast, learning schema-inconsistent information would require a more careful and gradual integration process to prevent interference with prior knowledge. The following evidence examines evidence from word learning studies manipulating the association between semantic information and prior knowledge.

The CLS prediction of schema-consistent benefits for rapid learning raises the question of what makes new information "consistent" with prior knowledge. Network-based approaches provide an account of the structure of semantic prior knowledge and its usage. Steyvers & Tenenbaum (2005) characterise semantic knowledge as a distributed network connecting words according to their semantic relatedness. In adults' mature semantic networks, word nodes are part of a sparsely connected network with strong local clustering, with a smaller number of words that serve as hubs to form links with many other nodes. One proposal suggests that new words are added to the network through preferential attachment, in which a new word is more likely to be learned if it is linked to a known word with many preexisting connections. In a paired-associative learning task, pseudowords were better remembered if they were paired with known words with more connections based on free association norms (Mak et al., 2021). Following this preferential attachment principle, novel words paired with semantic information that has richer connections should be learned more effectively than words paired with concepts that have fewer existing connections.

Developmental evidence suggests that even young children can leverage semantic network structure for learning. Hills et al. (2009) proposed that children, like adults, can benefit from preferential attachment and learn novel words that share more connections with existing knowledge. Children as young as 2 years of age can use familiar semantic categories and domains with richer word knowledge, such as animals, to support new word-object recognition (Borovsky et al., 2016). Specifically, the type of semantic information that supports learning changes across development: in early vocabulary learning, perceptual features predicted the age of acquisition of early words; whereas semantic information, such as functional or taxonomic features, becomes more beneficial in adulthood (Peters & Borovsky, 2019; P. C. Quinn & Eimas, 1997). This suggests that children's word learning with pictures may be particularly facilitated by visual semantic support that contains perceptual similarities with existing semantic connections.

Nevertheless, connecting new words to existing knowledge can also create interference effects through competition with semantically similar words during activation. Storkel and Adlof (2009) found that preschool children showed better recognition and recall of novel words when these words were paired with objects with a smaller semantic set size. Semantic set size was determined by a group of adults and children using an association task, with a smaller set size meaning there were fewer semantic neighbours that could induce competition with existing semantic representations and hinder the level of learning. A similar interference effect was also found in adults and children, who learned novel words paired with concepts made up of words with different numbers of semantic neighbours plus a novel feature (James et al., 2023). Adults' word form recall was impeded by higher semantic neighbourhood density; however, school-aged children were only impeded in meaning recall, but not word form recall. This developmental difference suggests that interference to word form from dense semantic neighbourhoods might increase with vocabulary development.

The distinctiveness hypothesis (Hunt & Mitchell, 1982) complements the interference perspective and suggests that items with unique or distinctive features can be encoded more effectively. Engelthaler and Hills (2017) found that words with more distinctive features are acquired earlier in development, but it is less clear how these complement the preferential attachment perspective outlined previously.

These findings suggest that semantic connections to existing knowledge can influence learning in multiple ways, with diverging predictions. Nevertheless, providing semantics through pictures alongside word forms at encoding has been a prevalent and helpful strategy to vocabulary and language learning in childhood (Breitfeld et al., 2021; Montag et al., 2015). The conditions under which facilitation and interference might be found remain unclear, though it is likely impacted by the type of association (broad categorical versus narrow similarity). Beyond the type of semantic connection with prior knowledge, other properties of semantic associations, including consistency and coherence, may also influence learning outcomes, as examined in the following section.

1.2.3 Other semantic factors that influence learning

The behavioural evidence discussed in the previous section suggests that there are benefits to including semantic information when learning new words. Beyond an all-or-nothing approach, the types of semantic relationships with prior knowledge can also influence the ease of learning new words. Thus far, the majority of the experimental work presented adopted an explicit, paired-associate learning approach. However, other studies have suggested that the consistency of this pairing can also affect word learning outcomes, along with contextual coherence when word meaning is provided indirectly through contextual cues during exposure.

When semantic information is provided through pictures or definitions, the consistency of word-referent mapping affects learning success. Hawkins et al. (2015) examined novel words that were learned with and without consistent semantic mapping using a semantic oddball task. Enhanced phonological discrimination was found in novel words with consistent mapping over inconsistent mapping in the immediate and the 1-day delay test. This demonstrates consistent word-referent association support initial encoding and long-term retention.

Rather than providing word-referent pairs through explicit teaching, an alternative approach focuses on adults' ability to extract word meaning from context. Batterink & Neville (2011) investigated the role of meaningful context in adults' novel word learning. Compared to words embedded in inconsistent text, novel words learned in semantically meaningful contexts showed higher recognition accuracy than in inconsistent contexts. Electrophysiological measures provided converging evidence, with novel words learned with meaningful context eliciting an N400 component similar to familiar words, indicating good integration into the existing lexicon. This demonstrates that semantically meaningful and coherent context facilitates both word form acquisition and integration.

Semantic consistency across multiple texts can also influence word learning. Wilkinson & Houston-Price (2013) proposed that multiple contexts would increase the number of connections with existing knowledge and result in a stronger representation compared to repeated contexts. This was later expanded by Mak et al. (2013), who identified the need for an initially low-diversity context, i.e. encountering new words across semantically similar passages, to act as "anchors" and provide a stabilising effect to novel words. Word learning can then take advantage of diverse contextual cues to further consolidate. Similarly, 3-year-old children also showed better immediate learning when novel words were embedded in the same story, which was repeated three times, compared to children who heard the novel words across three different stories (Horst et al., 2011). These findings suggest that while contextual cues facilitate learning across development, contextual consistency facilitates initial encoding and stabilisation, while a diverse context supports building a deeper representation.

1.3 Interaction between semantic factors and sleep consolidation to support word learning

An important theoretical consideration concerns the question of when "local" semantic prior knowledge benefits the timecourse of word learning. Prior knowledge could facilitate more efficient encoding and improve the success of later consolidation (Brodt et al., 2018). Yet, a different proposal suggests that prior knowledge benefits long-term learning through modulating sleep consolidation processes (Lewis & Durrant, 2011).

The CLS framework proposes that new information that is consistent with existing schemas will be embedded rapidly in long-term neocortical storage (McClelland, 2013).

According to this framework, if schema-inconsistent new knowledge is embedded directly in the distributed neocortical framework, the inconsistency can lead to interference with existing knowledge. Sleep provides an opportunity for offline replay and gradual integration to the neocortex, thus preventing interference. This model predicts that consistent information can be incorporated into the neocortex quickly, with little need for a more gradual sleep-dependent consolidation process, while inconsistent information would be learned more slowly and demonstrate greater improvements in integration following sleep consolidation opportunities.

In an alternative model, Lewis and Durrant (2011) propose that sleep processes contribute to the acquisition of both schema-consistent and inconsistent new knowledge. Their information overlap to abstract (iOtA) model suggests that sleep contributes to the abstraction process since newly acquired memories can reactivate during SWS without interference. Furthermore, neurochemical changes during SWS facilitate the transfer of information from hippocampal to long-term neocortical storage before resetting the hippocampus to create new learning capacity, creating a uniquely suitable environment for the integration of new memories. When new information has a greater overlap with existing schema, the iOtA model explains that they will be more strongly activated and result in a stronger, more distributed memory. Conversely, schema-inconsistent new information should form fewer connections with existing schemas and thus be more prone to decay. Following the iOtA model, new word forms learned with semantics should be learned and consolidated more readily than new word forms learned in isolation, since words learned with semantics would have more areas of overlap with existing schema.

Havas et al. (2018) verified the role of familiar semantics, rather than the presence of semantic information per se, in facilitating the learning of word forms. They compared three levels of semantic information: no semantics, unfamiliar picture, and familiar picture, in a word learning experiment using familiar and unfamiliar phonological structures. When word recognition was measured after a 12-hour delay, which either encompassed sleep or wakefulness, participants' recognition of words learned with familiar semantics was better than unfamiliar semantics, emphasising familiar semantics as the facilitatory factor. This benefit of familiar semantics is consistent with the predictions of the iOtA model, where familiar semantics supported stronger memory traces. However, as initial levels of learning were not measured, the specific time point when familiar semantic information is beneficial to word learning cannot be pinpointed in this study. The contribution of sleep consolidation processes appears to support the less well-learned items, as greater improvements after sleep were found in words with unfamiliar phonological structures. Alternatively, semantic and phonological information could follow different consolidation trajectories, with phonological form recognition being more dependent on overnight consolidation.

Further evidence in support of a selective role of sleep interacting with semantic knowledge on retaining memories of different encoding strength came from Payne et al. (2012), who compared participants learning semantically related and unrelated word pairs in the morning or the evening. The memory of the word pairs was evaluated after a 12-hour delay, which either encompassed a period of overnight sleep or daytime wakefulness. At the 12-hour retest, a sleep effect was found for the unrelated word pairs as the memory trace of these word pairs was maintained in the sleep group, compared to the wake group, whose memory of the unrelated word pairs deteriorated. This result suggested that sleep helped to protect the memory of unrelated word pairs from interference and deterioration, whereas related word pairs appeared to maintain a strong enough memory bond through their semantic link and were less prone to interference, therefore not requiring the protection of sleep processes. However, this pattern of results is contrary to the prediction of the iOtA model, as unrelated word pairs should have a smaller overlap of memories than related word pairs, but the sleep consolidation effect was found to be greater in unrelated word pairs. Nonetheless, word learning from Havas et al. (2018) and Payne et al. (2012) was only evaluated after a period of delay. The absence of an immediate post-learning test has therefore prevented the evaluation of predictions from the CLS model of rapid integration of consistent information prior to offline consolidation.

The role of visual referents on the long-term memory of novel word forms and their integration into the lexical network might be more complicated. Takashima et al. (2013) found a contrasting influence of pictures between tasks of explicit memory and integration, as recognition and recall showed greater overnight improvements for words trained with pictures, supporting the role of visual referents in enhancing verbal memory. Yet, delayed lexical competition effects emerged in the form-only group after 24 hours but not in the word-picture group, suggesting that the presence of pictures delayed the integration of novel word forms. Potentially, the pictures create additional consolidation demands and require more gradual integration to both lexical and semantic networks. Tamminen et al. (2013) showed that word meanings that are less likely to be inconsistent with prior knowledge can be acquired more rapidly when accompanied by greater spindle and slow wave activities.

They compared novel words with which the definitions form connections to sparse and dense semantic neighbourhoods and found a disadvantage for words with dense semantic neighbourhoods, as they were more likely to include inconsistent knowledge. Increased spindle activity and slow oscillation power for sparse semantic neighbourhood words were taken as an indicator of stronger integration.

There are relatively fewer studies focusing on the intersection between sleep consolidation mechanisms and semantic information from studies involving children. In one exception, Henderson et al. (2013) trained new words that were paired with or without semantic information in school-aged children. Semantic information was provided through explicit teaching of word definitions with pictorial referents. Explicit memory of the words improved after a 1-day delay, but no benefits were found for the presence of semantics at the immediate or 1-day tests. A semantic benefit was only found for word form recall after a 1-week delay, suggesting that semantic information stabilises the phonological form, leading to better long-term retention. Therefore, similar to adults, children's declarative memory of the word forms was strengthened over a period of consolidation, with the presence of semantic information providing a stabilising effect.

With that being said, semantics could also exert an overall benefit to children's and adults' word learning. James et al. (2023) used the same semantic neighbourhood manipulation as Tamminen et al. (2013) in a word learning study with adults and school-aged children. Benefits for sparse semantic neighbourhoods were found for the meaning recall task for children and the word form recall for adults. Critically, these benefits were demonstrated at the immediate test for both age groups and persisted across consolidation, even when recall performance improved for adults' form recall. The nature of semantic associations may determine when benefits emerge. For studies comparing the presence and absence of semantic support, the effects of semantic support may be confounded with differences in learning demands. However, when different semantic associations are compared, such as between semantic neighbourhoods or the extent to which connections with prior knowledge can be made based on visual features, connections to local semantic knowledge may demonstrate immediate encoding advantages, forming a stronger representation rapidly, rather than requiring offline consolidation opportunities.

1.4 Individual Differences in "global" language skills

Earlier parts of this review outlined the general effects of sleep and semantic information for acquiring new vocabulary in adults and children. Nonetheless, individual differences in "global" language skills, which reflect both the capacity to learn and the breadth and depth of existing knowledge, can also influence the rate and success of word learning. While studies manipulating different levels of semantic input have suggested that manipulating the nature of the semantic relationships of novel words can lead to different learning outcomes, the level of learning also depends on the existing knowledge of the learners. Complementary approaches which manipulate the level of semantic information available to participants and also measure individual differences in pre-existing relevant knowledge and skills, such as vocabulary knowledge, can provide a more comprehensive view of how different semantic factors interact.

1.4.1 Individual Differences in Vocabulary Knowledge

One source of individual differences comes from existing vocabulary knowledge, which underpins overnight improvements in consolidating newly acquired word forms. In the reading and literacy development literature, the idea of the "Matthew Effect" suggests that children with better reading abilities and vocabulary are more likely to read more and to acquire new vocabulary through reading (Cain & Oakhill, 2011; Stanovich, 1986). This results in a long-term widening of the vocabulary gap among children, with greater vocabulary growth in children with better literacy and vocabulary knowledge (although see Pfost et al., 2014 for suggestions that this relationship may be less straightforward). In terms of word learning and consolidation, a meta-analysis of the correlation of standardised vocabulary scores and overnight changes in lexical competition showed greater overnight improvements in lexical integration among children with better existing vocabulary (James et al., 2017).

Apart from overnight improvements in lexical integration, the benefits of having stronger vocabulary knowledge were also reflected in explicit word form recall. While all the child participants showed improvements in the recall of newly learned word forms and an increase in lexical competition, children with better expressive vocabulary showed greater improvements in both of these measures (Henderson et al., 2015). Furthermore, Landi et al. (2018) provided neural evidence for the role of vocabulary in consolidation: adolescents with better reading and vocabulary skills showed greater consolidation-related brain activation in regions implicated in memory retrieval when recognising words learned in the previous days compared to words learned immediately before testing. This provides a potential mechanistic explanation behind the "Matthew Effect" as an interaction between existing knowledge and sleep-mediated consolidation processes in children and adolescents.

Conversely, recent evidence suggests that vocabulary influences overall word learning performance across the timecourse of word learning. James et al. (2021) found that vocabulary ability predicted children's and adults' word form recall across test sessions, with the benefit of good vocabulary being maintained among different phonological neighbourhood conditions. This general association between vocabulary and word learning performance maintained across test sessions suggests that existing vocabulary could provide a word learning advantage rather than specifically enhancing consolidation. Similarly, vocabulary and reading skills can also predict encoding efficiency, as adolescent participants with better vocabulary and reading skills required fewer training blocks to reach criterion during initial training (Landi et al., 2018). Furthermore, Adlof and Patten (2017) showed that vocabulary knowledge, along with nonword repetition, a measure of phonological working memory and encoding capacity, predicted children's recall and recognition of the phonological and semantic aspects of the words learned within the same session. While both vocabulary and nonword repetition predicted recall and recognition, vocabulary was a stronger predictor of recalling the semantic aspects, such as describing the corresponding referent, whereas nonword repetition explained more variance in the recall and recognition of phonological form.

The lexical restructuring hypothesis (Metsala & Walley, 1998) provides a mechanism by which existing vocabulary may support overall word learning. A growing vocabulary demands phonological representations to become increasingly well-defined to better distinguish between similar-sounding words. Additionally, having a larger vocabulary could reflect richer semantic networks for integrating new words, akin to adults having a more extensive semantic network than children, which allows adults to use prior knowledge to support learning more effectively (See Section 1.2). Therefore, while it is unclear what factors determine a general effect of vocabulary benefiting overall word learning or a specific effect of vocabulary on overnight consolidation processes, both of these mechanisms suggest that children with better vocabulary can make use of this knowledge to achieve cumulative success in expanding their lexical network.

1.4.2 Word learning in adults and children with literacy weaknesses

While adults and children with typical development vary in their vocabulary knowledge and the rate of acquiring new words, individuals with language weaknesses experience greater challenges in learning. Sleep disturbances have been reported across multiple communication and language disorders (e.g. autism spectrum disorder: Botting & Baraka, 2018; developmental dyslexia: Carotenuto et al., 2016); therefore, individuals with these developmental conditions may demonstrate limited overnight consolidation effects as a result of poorer sleep and differences in sleep architecture. This is in addition to variations in word learning among adults and children with varying language skills (Bishop et al., 2012; Gordon et al., 2022).

Phonological weaknesses are a hallmark of dyslexia, and behavioural evidence demonstrates that both adults and children with dyslexia experience increased difficulties in word learning, especially in acquiring the phonological forms (Henderson et al., 2013; Ouellette & Fraser, 2009). In terms of their consolidation abilities, Smith et al. (2018) provided critical insights into the sleep consolidation of novel words in children with dyslexia. While there were no apparent group differences between children with and without dyslexia in sleep architecture per se, the association between sleep parameters and changes in recall was only found in children without dyslexia. This suggests that children with dyslexia are less able to engage active systems to benefit from sleep consolidation processes. The comparison between children with dyslexia and a younger group of typically developing children further suggests compromised long-term consolidation capacities in children with dyslexia, as their rate of improvement at the 1-week delay test lagged behind that of typically developing children matched on initial levels of performance.

In comparison to phonological processing, semantic skills are relatively less impacted in dyslexia (Bishop & Snowling, 2004; Bradshaw et al., 2021), with some adults with dyslexia showing well-developed vocabulary skills, comparable to non-dyslexic adults (Cavalli et al., 2016). This opens the possibility that individuals with dyslexia can benefit from semantics to a similar extent as peers without phonological weaknesses during word learning. Semantics may even provide an alternative pathway for learning: Savill et al. (2019) demonstrated that adults with weaker phonological skills increased their reliance on lexical-semantic knowledge to support short-term retention of phonological sequence during immediate serial recall tasks. However, whether this increased reliance can act as a compensatory mechanism to support word learning remains an open question.

1.5 Concluding remarks and thesis outline

The literature reviewed in the preceding sections establishes that both memory consolidation and semantic associations influence word learning, with varying importance across the developmental trajectory. Children demonstrate superior overnight consolidation compared to adults, potentially reflecting greater slow wave sleep in childhood. Semantic information presented alongside word forms during learning enables deeper connections to be formed, with adults having accumulated more extensive prior knowledge, enabling them to create links more readily with their existing semantic network. Existing literature has indicated a role of existing vocabulary in the consolidation process, but further research is needed to explore how vocabulary knowledge supports word learning differently across development.

The present thesis addresses the critical empirical gap of when prior knowledge benefits word learning across development, examining the influence of prior knowledge within word learning and consolidation across one week and developmental differences between adults and children aged 9 to 11, an age group that has shown the most robust sleep consolidation effects. Memories are assessed immediately after learning and after delays encompassing different consolidation opportunities (10-minute retention period, 1-day delay and 1-week delay) to determine when semantic effects emerge and how consolidation may differ between age groups across different consolidation windows. Whilst this design does not directly manipulate sleep versus wake (e.g. Dumay & Gaskell, 2007; Havas et al., 2018), this approach captures naturalistic consolidation encompassing both processes. Word learning is assessed primarily by the explicit recall of word forms through the provision of partial lexical (phonological or orthographic) cues and picture naming. Explicit recall tasks are chosen as consolidation effects are more robust in measures involving recollection compared to recognition or implicit tasks (Drosopoulos et al., 2005). The focus on word-form memory reveals whether semantic information provided during learning transfers to support lexical representations and retrieval under different task demands.

Local connections with prior semantic knowledge are manipulated by pairing novel words with pictures varying in the amount of support from existing knowledge (highly linkable pictures resembling familiar animals vs less linkable pictures depicting fictitious creatures). The diverging predictions of theoretical frameworks on the timecourse of prior knowledge benefits motivate an examination of whether semantic benefits can be found early in word learning, i.e. at an immediate test shortly following word learning, or if a period of delay is required. Using pictures as semantic referents rather than written definitions or lexical context reduces linguistic demands, enabling examination across adults and children with varying language profiles, including those with weaker literacy skills. This approach minimises demands on literacy and phonological processing, isolating the contribution of semantic information and revealing how learners extract semantic information and form connections with prior knowledge. Beyond theoretical contributions to word learning models, these directions have the potential to inform vocabulary instructions provided at schools by distinguishing whether students with weak vocabulary struggle with forming semantic connections or with the additional linguistic skills required in typical learning contexts.

Individual differences in language abilities will also be examined using standardised assessments, focusing on how variations in vocabulary skills (measured through receptive and expressive vocabulary tasks) relate to adults' and children's use of semantic information, consolidation trajectory and overall learning outcomes. The contributions of other linguistic skills, including phonological working memory (as measured by the nonword repetition task) and literacy skills (as measured by decoding, reading and spelling tasks) will also be explored. Examining a range of linguistic skills alongside the manipulations of semantic support and consolidation timeframes can help clarify the interaction of "global" prior knowledge with "local" semantic connections in shaping learning.

Chapter 2 focuses on whether providing meaningful pictures alongside new word forms enhances word learning, and whether closer links with prior knowledge may provide additional benefits across one week. The two experiments in this chapter examined whether these local semantic benefits can be found immediately after learning, after a one-day and a 1-week delay in children aged 9 to 11 (Experiment 1) and adults (Experiment 2). Developmental comparisons were also conducted to replicate children's larger consolidation benefit from previous studies and explore if the role of semantics differs across development. To enable direct comparison, adults' initial levels of performance were matched with children's by reducing the amount of training given to adults. The impact of individual differences in receptive vocabulary and nonword repetition was also examined to further examine potential drivers of variation in children's word learning.

In Chapter 3, we focus on the developmental differences in consolidation, examining wake-based memory stabilisation as a potential mechanism contributing to children's greater improvement across one week. This allows us to examine whether other memory consolidation mechanisms may be enhanced in childhood, alongside sleep-based active systems consolidation. We conducted two experiments where children aged 9-10 (Experiment 3) and adults (Experiment 4) engaged in 10 minutes of either wakeful rest or spot-the-difference puzzles after learning novel words. Word form recall and picture naming were tested before and after the 10-minute period, to assess the memory benefits of wakeful rest compared to spot-the-difference puzzles, as well as the long-term benefit of this stabilisation opportunity after one week. Individual differences in the expressive vocabulary of adults and children were used to explore whether wakeful rest may be particularly beneficial for individuals with weaker or stronger vocabulary skills.

Chapter 4 examined the role of prior knowledge in adults' new word learning and recall by taking an individual differences approach. We focused on understanding novel word consolidation across one week in adults with a broad range of literacy skills and aimed to replicate the local semantic benefit for words which are more linkable to prior knowledge in this sample. Additionally, we explored whether adults with weaker language and literacy skills might show greater reliance on semantic connections in novel word learning. Adults' recall was examined immediately after learning and after a 1-week delay, without the interim retrieval and retesting opportunities included in earlier experiments.

Through five experiments across three studies, we examine the underlying processes by which semantic information supports vocabulary learning, and how these processes vary across development and individual differences in linguistic skills.

Chapter 2 Developmental Differences In The Timecourse Of Word Learning

This chapter was previously published as:

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The data files and scripts for the pre-registered and exploratory analyses can be found at https://osf.io/gruc4/. Pre-registrations can be found at https://osf.io/xkbnz (Experiment 1) and https://osf.io/w6mvp (Experiment 2).

2.1 Abstract

Theories of memory consolidation claim that new word learning is bolstered by existing semantic knowledge. However, *when* semantic knowledge exerts its effects (i.e., at encoding and/or consolidation) and whether semantic benefits change across development remains unclear. Sixty-one children (Experiment 1) and 63 adults (Experiment 2) learned novel word forms paired with pictures of (i) real but rare animals akin to existing animals (Highly Linkable to existing knowledge), (ii) fictitious animals that were less clearly associated with familiar animals (Less Linkable), and (iii) "name tags" written with unfamiliar symbols (Unlinkable). Word form and meaning recall were tested immediately, 1 day and 1 week after learning. Children showed greater improvements across tests than adults despite comparable performance immediately after learning. Regardless of test sessions, semantic knowledge benefited adults' recall of word form and meaning, with additional benefit from highly versus less linkable knowledge. Children only showed semantic benefits in meaning (and not word form) recall, with additional benefits from highly linkable knowledge. Instead, children's word form recall was more globally associated with receptive vocabulary and nonword repetition. These results suggest that when present, the benefits of semantic information permeate across the timecourse of word learning; they also point to

developmental differences in word learning mechanisms. Adults made clear use of associated semantic knowledge, whereas children showed more general associations between word learning and language abilities and greater benefit from offline consolidation. These results highlight the need for models of word learning and consolidation to incorporate developmental and individual differences.

2.2 Introduction

Forming a robust long-term memory of a word form and its meaning so that it can be efficiently and flexibly retrieved for communication purposes is the ultimate goal of word learning. While new words can be encoded with minimal exposure (Mak et al., 2021), overwhelming evidence suggests that effective long-term memory formation, including the integration of a new word within existing lexical networks, is a gradual process that benefits from repeated presentation (Nation et al., 2007), retrieval practice (Antony et al., 2017) and sleep consolidation processes (James et al., 2017). However, word learning success is implicated by multiple factors, both intrinsic and extrinsic to the learner. For instance, word learning is influenced by prior knowledge, such as learning material that aligns closely with existing semantic information (Craik & Lockhart, 1972; McClelland, 2013). Here, we examine two critical questions regarding the role of semantics in word learning, key to advancing theory and applying this to optimising word learning in pedagogical contexts: *when* in the timecourse of word learning does existing semantic knowledge exert its effect, and *who* benefits the most from such knowledge?

2.2.1 Word Learning Through the Lens of Memory Consolidation

Models of memory provide domain-general frameworks for understanding the word acquisition process across stages of encoding, consolidation, and retrieval. The Complementary Learning Systems (CLS) framework (Henderson et al., 2012) proposes dual memory systems underpinned by different neurobiological substrates, which work together to enable rapid encoding, long-term retention and integration with existing knowledge. Specifically, a hippocampal-based system supports rapid storage of information in a sparse, encapsulated manner. Information is then integrated gradually with prior knowledge in the neocortex to avoid interference with and disruption to existing knowledge. The CLS framework has been applied to language processing (Gaskell et al., 2019; Mak et al., 2023), and specifically to word learning. Novel word representations, similar to episodic memory, benefit from sleep-related consolidation during which new representations in the hippocampus are integrated with the neocortical system, thus facilitating their subsequent recall and recognition (Davis & Gaskell, 2009; Tamminen & Gaskell, 2013).

While the CLS framework was developed utilising adult data, children also showed similar sleep-associated improvements in word learning. For instance, word form recall and lexical integration improve after sleep, but not across equivalent time awake (Henderson et al., 2012). Moreover, a greater improvement in word recall across multiple days in children than in adults (James et al., 2019) suggests that children receive greater benefits from offline consolidation than adults. However, these developmental differences have mainly been demonstrated through learning new word forms in isolation (James et al., 2019; van Rijn et al., 2023) or through incidental exposure through stories (James et al., 2021); it is less clear whether learning new word *meanings* follows comparable consolidation trajectories and shows similar developmental differences.

Emerging evidence suggests that larger offline consolidation benefits for children in word learning do not occur over repeat tests within the same day and only occur over several days (Olsson, 2022). One theory suggests that these effects may be specifically attributed to sleep (James et al., 2017). The proportion of slow wave sleep (SWS) decreases with age after reaching a peak in children aged 10-12 years, averaging roughly double the proportion of SWS relative to adults (Ohayon et al., 2004). Critically, slow wave oscillations and temporally aligned sleep spindles are associated with overnight improvements in word recall and lexical integration (F. R. H. Smith et al., 2018; Tamminen et al., 2013) in children and adults. For instance, in a polysomnography study, Smith et al. (2018) showed that slow wave activity and spindle power predicted typically developing children's post-sleep word recall, while spindle power was also predictive of the gains in lexical competition. As these neural activities represent reactivations of newly learned information during sleep, this provides evidence for the active consolidation of newly learned words and their incorporation into children's lexicon.

There may also be alternative, not necessarily mutually exclusive, explanations for increased offline benefits in children. For instance, sleep provides a period free from interference, thus preserving memory and preventing forgetting, which may be more beneficial for children (see van Rijn et al., 2023 for further discussion). Furthermore, experimental designs with repeated testing elements provide additional consolidation benefits through retrieval, even in the absence of feedback (Antony et al., 2017; Roediger & Butler, 2011), and it remains plausible that children may benefit more from repeated retrieval opportunities than adults.

2.2.2 Consistency with Prior Semantic Knowledge

Providing explicit semantic information alongside new word forms benefits word learning, as it enables more in-depth processing than when word forms are presented without meaning (Craik & Lockhart, 1972). For example, presenting new spoken words with picture referents and definitions led to better word recall one week after learning, compared to presenting new spoken words with only their orthographic forms in children aged 5-9 years (Henderson et al., 2013; Ouellette & Fraser, 2009). This suggests that the availability of semantic information, whether it be an object referent or a definition, can facilitate the memory of new lexical representations.

Theories of learning and memory diverge on *when* the influence of semantics might emerge in the word learning process. In an extension to the original CLS framework, McClelland (2013) proposed that consistency with schema, or existing knowledge, allows new information to be integrated into long-term storage sites more rapidly and is less reliant on hippocampal temporary storage (Tse et al., 2007). Thus, while CLS does not explicitly address the role of sleep in the timecourse of memory integration, it aligns with the prediction that learning new words associated with consistent existing semantic knowledge could show early benefits, even before sleep. Alternatively, the Information Overlap to Abstract (iOtA) model (Lewis & Durrant, 2011) proposes a sleep-based mechanism for forming new schemas and for assimilating new memories into existing schemas during offline reactivation in sleep. This perspective predicts a greater benefit of learning information consistent with prior knowledge *after* a period of sleep. Therefore, one can derive specific predictions about the timecourse of semantic benefits for word learning from these two models of memory, and the present study aims to shed light on these theories by examining the timescale of consolidation of novel words with different amounts of semantic information.

In one of the few studies to examine when consolidation may be supported by familiar semantics, Havas et al. (2018) examined word learning with familiar objects, novel objects, and without pictures. Better recognition of word forms and word-picture correspondence of familiar semantics was found after a 12-hour delay, regardless of whether it included sleep or wakefulness. However, the lack of an immediate test following learning makes it impossible to determine whether the advantages of familiar semantics were immediate, or whether they only emerged after a delayed period.

Using existing knowledge to support word learning may be partly dependent on the size and richness of the existing knowledge network, leading us to predict both developmental and individual differences in the benefit of semantics on word learning. For instance, adults - with more extensive lexical and semantic networks - may draw on top-down support from their richer networks to support word learning (Bermúdez-Margaretto et al., 2020). Conversely, children - receiving less support from a developing lexicon - may rely more on alternative mechanisms, such as memory consolidation processes (James et al., 2017). This would be consistent with the evidence discussed above that children demonstrate greater consolidation across time than adults (Wilhelm et al., 2013). Moreover, James et al. (2019) showed larger gains in children's new word recall over a week than adults', while adults showed lasting benefits from learning new words with more orthographic and phonological neighbours - compared to children who only showed such benefits at immediate test, with consolidation gains allowing no-neighbour words to catch up. However, given this neighbourhood manipulation did not specifically target semantic knowledge, it remains unclear if and when children show less support from semantic knowledge in word learning.

Individual differences in prior knowledge among children, specifically vocabulary knowledge, are associated with word acquisition. This is referred to as the "Matthew Effect" in vocabulary development, whereby "the rich get richer" as children with better vocabulary skills are better equipped to learn and retain new words, resulting in a widening vocabulary gap (Cain & Oakhill, 2011; James et al., 2017; Stanovich, 1986). Consolidation mechanisms could underlie the Matthew Effect, such that children with better vocabulary knowledge are superior at overnight consolidation, as evident by positive correlations between children's vocabulary knowledge and overnight gains in new word recall and lexical integration (Henderson & James, 2018; James et al., 2017). Among younger children, a larger vocabulary is beneficial for learning novel labels and objects in familiar categories (Borovsky et al., 2016), suggesting that individual differences in vocabulary knowledge impact the ability to capitalise on connections with semantic knowledge to support learning and consolidation (Diakidoy, 1998). Alternatively, the Matthew Effect may manifest as a general language learning benefit, as children with better vocabulary knowledge on standardised tests perform more accurately on measures of new word learning across test sessions (James et al., 2021). This could be a reflection of variabilities in general language ability, as phonological skills such as phonological memory capacity (as measured by nonword repetition) also impact the construction of new word forms in both children and adults with and without language impairments (Bishop et al., 2012). Consistent with this, prior research suggests that vocabulary and nonword repetition predict different aspects of word learning, as vocabulary size was a predictor of semantic recall while nonword repetition predicted word recall and recognition (Adlof & Patten, 2017). Taken together, developmental differences may be present in the learning trajectory of new words between adults and children as well as within-age-group individual differences: adults may show better learning of new words that receive greater support from existing semantic knowledge, possibly earlier in the learning process, whereas consolidation across multiple days may be more beneficial to children.

2.2.3 The Present Study

In two pre-registered experiments, we manipulated the extent to which new word meanings may form links with, and receive support from, existing knowledge during word learning. Using a within-subjects design, children aged 9 to 11 (Experiment 1) and adults (Experiment 2) learned new spoken word forms that were paired with picture referents from three semantic conditions (Highly Linkable, Less Linkable & Unlinkable) and their recall of word forms and meanings were assessed immediately following learning, after 1 day and after 1 week. This allowed for the examination of whether children and adults follow different learning trajectories for words receiving different levels of semantic knowledge support. The three semantic conditions manipulated the information available from picture referents presented with novel words: (i) rare animals that were selected to be similar to already-familiar animals (i.e., Highly Linkable), (ii) fictitious animals that were created to be dissimilar to known animals (i.e., Less Linkable) and (iii) "animal name tags" that comprised coloured geometric backgrounds with superimposed unfamiliar Taiwanese *zhuyin* symbols, which provide a visual cue but contain no animal-related content (i.e., Unlinkable). Crucially, these conditions were designed to manipulate the extent to which connections could be formed with existing knowledge. Similar to Havas et al. (2018), the three semantic conditions allow us to contrast the absence of meaningful semantics in the Unlinkable condition with the presence of meaningful semantic information in the Less and Highly Linkable conditions. Any difference between these conditions will highlight the contribution of prior knowledge in supporting word learning. We expected the easiest connection with existing semantic knowledge in the Highly Linkable condition, harder to form existing semantic connections with the Less Linkable condition, and most difficult to form semantic connections in the Unlinkable condition.

The present study examined the effect of semantic information on the recall of new word forms and meanings. Based on prior studies (Henderson et al., 2013; James et al., 2019), we anticipated that recall would improve across test sessions, benefiting from both offline consolidation and repeated testing opportunities. It should be noted that studies adopting designs that can isolate the effects of sleep from repeated testing (Dumay & Gaskell, 2007; Havas et al., 2018; Henderson et al., 2012) have demonstrated additional sleep-consolidation benefits which cannot be explained by repeated testing effects alone. To allow room for improvements across one week, we aimed for a lower performance at the initial test, consistent with previous studies with a similar design (e.g. James et al., 2019, 2021).

To facilitate developmental comparison, we matched the initial performance in word form recall by reducing the amount of exposure to the word forms during training in adults (five exposures for adults, eight for children). This approach directly compares the effects of existing knowledge support and offline consolidation between adults and children across test sessions without the confounding effects of different levels of initial encoding; this is important because lower levels of initial encoding can lead to larger consolidation effects (Drosopoulos et al., 2007). We expected improvements in both adults and children, but children would benefit more from offline consolidation processes and show greater improvements across the three test sessions compared to adults. At the same time, since adults have accumulated richer existing semantic knowledge and a mature language processing system, we predicted that this would enable them to benefit more from semantic information, particularly when it is highly consistent with existing knowledge.

Finally, we investigated individual differences in children's word learning. While manipulating the semantic information of the stimuli allows us to see if children and adults equally benefit from these local semantic associations, the incorporation of standardised measures informs whether the consolidation of word form and meaning recall is specifically associated with vocabulary knowledge (James et al., 2017) or more globally associated with language skills, such as phonological memory.

2.3 Experiment 1 - Children

We tested the following pre-registered hypotheses with typically developing children aged 9 to 11 (Pre-registration available at: https://osf.io/xkbnz/):

H1. Newly learned word forms would be better recalled at the 1-day and the 1-week delayed test sessions than immediately following training, as the later test sessions can benefit from overnight consolidation and repeated testing. As there were further opportunities for offline consolidation and retrieval practice by the 1-week test, we hypothesised continued improvements in memory of new words at the 1-week delay test compared to the 1-day delay test.

H2. We predicted that items paired with semantic information (i.e. Highly Linkable and Less Linkable conditions) would be better learned than items paired with patterns (i.e. Unlinkable condition).

H3. We predicted that the better learning of the words paired with pictures from the Highly Linkable than the Less Linkable condition could either manifest at the immediate test and show reduced improvement from immediate to 1-day delay tests (following the CLS framework) or the benefit could manifest through increased improvement from immediate to 1-day delay tests (according to the iOtA model).

H4. Children with better receptive vocabulary would demonstrate greater improvements, both overnight and across one week, in the recall of word forms and form-meaning correspondence. As an exploratory analysis, we also considered language skills beyond vocabulary, using nonword repetition as a measure of phonological memory predicting word form and meaning recall.

2.3.1 Experiment 1 Methods

Participants

Our pre-registration specified the sample size as 60 children, based on an *a priori* power analysis with G*Power (Version 3.1.9.6, Faul et al., 2007) following the interaction between semantic condition and test session ($\eta_p^2 = .22$) in Henderson et al. (2013), at a significance criterion of $\alpha = .05$ and power = .90.

Sixty-one children (31 boys and 30 girls) aged 9-11 years (*M* = 10.08 years) were recruited from a mainstream primary school in North Yorkshire, United Kingdom. Fifty-nine of the participants were native monolingual English speakers, with two bilingual speakers of English with Thai and Hungarian, respectively. Both children reported using English at school and in everyday communication, and their performance in standardised language tests (the British Picture Vocabulary Scale, 2nd Ed; Dunn et al., 1997) was within the normal range. Therefore, their data were retained in the analysis.

The study was approved by the Research Ethics Committee of the Department of Psychology. Consent was obtained from the school headteacher, and parents were fully informed and provided opt-out consent.

Stimuli

Twenty-four novel words were paired with a picture from one of three categories: Highly Linkable animals, Less Linkable animals and Unlinkable patterns. All stimuli were placed on a 1080 x 1080 pixel square canvas with a plain white background (see Figure 1). Animals for the Highly Linkable and Less Linkable conditions were digitally drawn in coloured using Procreate (version 5.2.6, Savage Interactive, 2022).

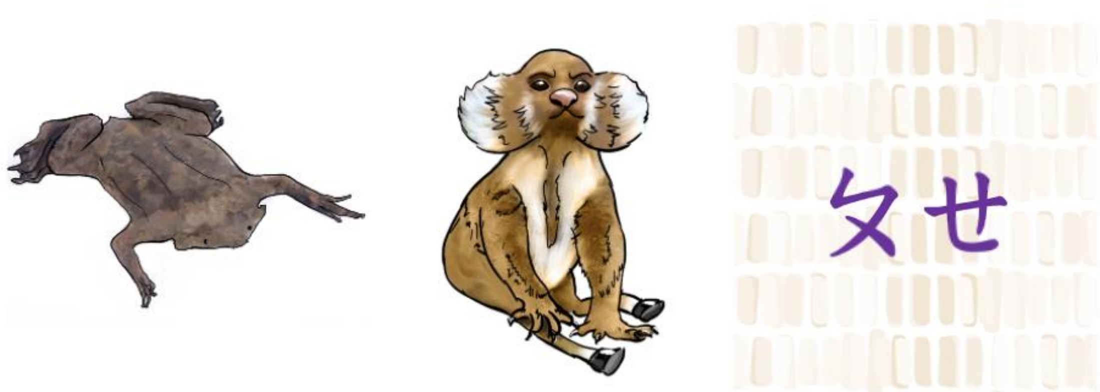


Figure 1 Examples of picture stimuli for each semantic condition in Experiments 1 and 2 (Left to Right: Highly Linkable, Less Linkable & Unlinkable)

Highly Linkable animals

The Highly Linkable stimuli were real breeds or species of animals that were deemed by the researchers to be unfamiliar to children aged 9 to 12 years. They were characterised by being easily associated with a familiar animal while having at least one unique physical feature that set it apart from that familiar animal (e.g. a *pipa* is a frog with a very flat body). Two pilot studies with 31 adults and 10 children (aged 8 to 12) were used to verify that the selected animals were unfamiliar to adults and children but could be consistently related to similar familiar animals (e.g. pilot participants consistently deemed a *pipa* as similar to a frog, see Appendix A).

Less Linkable animals

The Less Linkable stimuli were fictitious animals consisting of at least one salient feature (e.g., big, chubby cheeks), created by combining features and textures from different animals such that they did not consistently resemble any single familiar animal. The aforementioned pilot studies verified that these animals were unfamiliar to adults and children and enabled the selection of 8 stimuli that could not be associated consistently with familiar animals.

Unlinkable patterns

Each picture in the Unlinkable condition consisted of a patterned background and two symbols adopted from the Taiwan *zhuyin* phonetic system. These symbols were used so that they provided a similar number of distinctive but meaningless features for participants to identify and recall. A different colour combination was used for each background and symbol combination as global features. The symbols on each stimulus (albeit unfamiliar to the participants) did not match the sounds of the nonwords they were paired with.

Novel Word Stimuli

Twenty-four bi- or tri-syllabic words were selected, with 8 items (*jerboa, kochi, loaghtan, mata, okapi, pinchaque, pipa, zebu*) being the names or part of the common or scientific names of the animals selected for the Highly Linkable condition. The remaining items consisted of two lists of 8 nonwords adopted from the items in the Phonemic Decoding Efficiency subtest of the Test of Word Reading Efficiency (2nd Ed; Torgesen et al., 2012) and unusual names from the Novel Object and Unusual Name Database (Horst & Hout, 2016). Each list of the nonwords was matched in the number of syllables, bigram frequency and initial syllable, and items in each list were either paired with stimuli from the Less Linkable or Unlinkable conditions. They were recorded by a female native British English speaker.

Procedure

All participants were tested at three time points: immediately after learning (T1), after a one-day delay (T2), and after a one-week delay (T3). T3 took place 6 to 9 days (M = 7.8 days) after the first session, except for 3 children, who completed the final test 12 to 14 days after the first session due to absences from school. Data collection took place individually, either in an empty classroom or in a quiet place in school during school hours. All experimental tasks were presented using Gorilla Experiment Builder (Anwyl-Irvine et al., 2020) on a 14" Macintosh laptop. The words were presented via a pair of headphones, and children responded either by pressing buttons on a keyboard or verbally to the attached microphone for later offline transcription and coding.

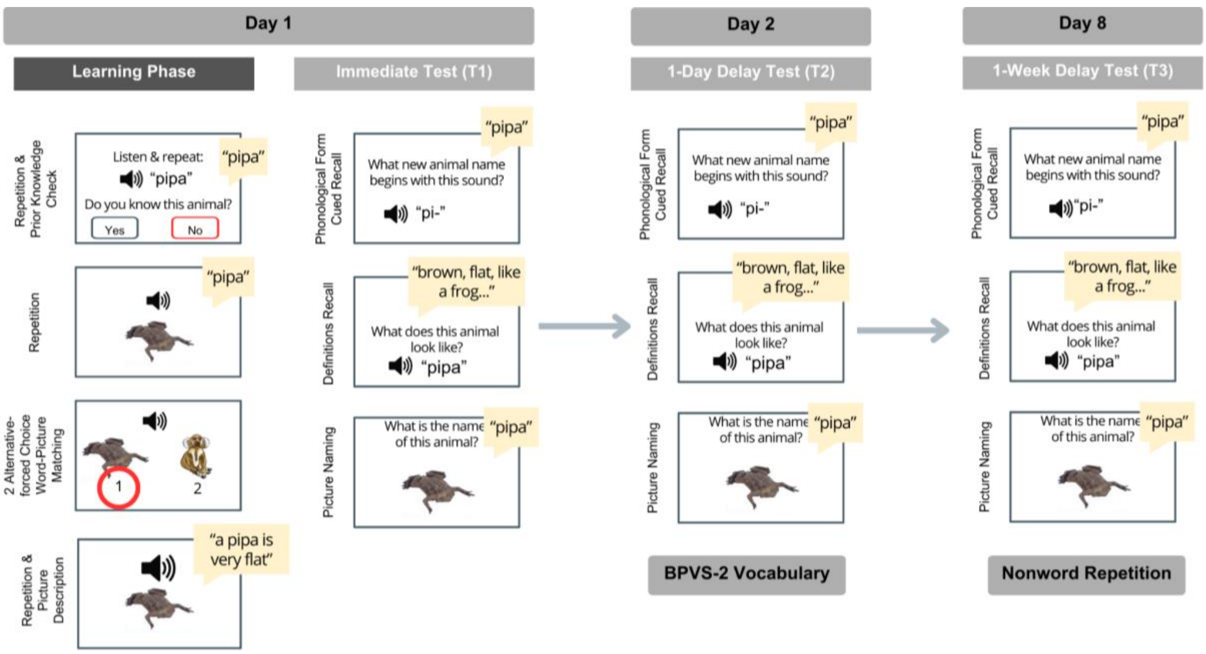


Figure 2 Overview of the procedure for Experiments 1 & 2.
BPVS-2 Vocabulary and CTOPP-2 nonword repetition were only conducted with children in Experiment 1

Learning Phase

Four training tasks were used to familiarise children with phonological forms and pictures (see Figure 2). In total, children heard each new word eight times, saw each picture six times and received three repetition opportunities.

Repetition and prior knowledge check

Children heard each new word and repeated it aloud. They were then asked to indicate whether they knew the meaning of the words and, if they did, to briefly describe the animal to demonstrate their knowledge. If their descriptions demonstrated any knowledge of the target animal (even limited, e.g., alluding to a *pipa* as an amphibian), they were removed from analysis.

Word repetition

Children heard each new word with the corresponding picture stimuli presented on the screen. They repeated the words aloud and then heard the word again through the headphones.

Two-alternative forced-choice (2AFC) word picture-matching

In each trial, children heard a word and were presented on-screen with a target picture that matched the word and a distractor picture corresponding to another word belonging to one of the three semantic conditions. The numbers "1" and "2" appeared beneath each picture. Children were asked to select the picture that matched the word they heard by pressing the corresponding number key. Feedback was given through the presentation of the word with the correct picture on the screen for 3000ms. Children completed two blocks of the picture-matching task, with a different distractor picture paired with the target in each block.

Repetition and picture description

Each new word was presented via headphones with the respective picture on the screen. Children were asked to repeat the word aloud and to provide one physical description of the picture (e.g. "A *pipa* is very flat"). This task aimed to orient the participants towards the features embedded in the target picture.

Testing Phase

Three tasks were used to examine children's knowledge of the word forms and meanings. The tasks were presented in each test session in a fixed order, with the items within each test presented in a randomised order.

Phonological cued recall

Children heard the first consonant(s) and vowel of the target word and were asked to complete the rest of the word. They were encouraged to give partial responses and make guesses if they were not sure of the answer. Responses were transcribed and scored based on accurate completion of the target word (0 or 1).

Definition recall

Children were presented with a word and were asked to describe the corresponding animal or pattern with as many details as they could recall. Responses were transcribed, and a lenient scoring system was adopted (Hulme & Rodd, 2021). That is, a response received a score of "1" if at least one feature was recalled that allowed for the correct identification of the target picture within the stimulus set, as confirmed by two independent scorers. Inter-rater reliability was calculated using Cohen's kappa, $\kappa = .80$, suggesting strong agreement between scorers (McHugh, 2012). Ambiguous and conflicting responses were resolved on a case-by-case basis via discussion between the scorers.

Picture naming

A picture of an animal or pattern was presented on the screen, and children were asked to recall the corresponding word. Partial responses and guesses were encouraged if they were unsure. Responses were transcribed and were scored based on whole-word accuracy (0, 1).

Standardised Tests

The British Picture Vocabulary Scale, 2nd edition (BPVS-2, Dunn et al., 1997) and the nonword repetition subtest of the Comprehensive Test of Phonological Processing, 2nd edition (CTOPP-2; Wagner et al., 2013), were administered at T2 and T3 to measure children's vocabulary knowledge and phonological working memory. Responses for the two standardised tests were scored and converted to standard scores as per the test manuals.

Data Analysis

All data were analysed in RStudio (version 2021.09; RStudio Team, 2020) for R version 3.6.1 (R Core Team, 2024) with lme4 (Bates et al., 2025) and emmeans (Lenth et al., 2025) packages. Graphs were created using *ggplot2* (Wickham et al., 2024).

Items for which participants indicated prior knowledge during training were excluded from analysis, amounting to 30 out of 1464 total words or 2% of all data points removed from analyses. For each task in the testing phase, a model with fixed effects of test session, semantic training condition, BPVS standard score centred at pre-processing, and their interactions was fitted. As a three-level factor, two repeated contrasts were created for test sessions: 1) T1vsT2: for differences in performance immediately after learning and after a 1-day delay; 2) T2vsT3: for subsequent changes across a longer period of delay, between the 1-day delay and 1-week delay tests. For semantic training conditions, Helmert contrasts with 2 levels were set to evaluate performance differences, i) Semantics1: between words paired with patterns in the Unlinkable condition and animals (both Highly and Less Linkable), and 2) Semantics2: between words paired with animals from the Highly and Less Linkable conditions.

After establishing the best-fitting mixed effects model, standardised dfbetas were calculated to identify influential cases using the package influence.ME (Nieuwenhuis et al., 2012). Participants with a standardised dfbeta beyond ±3.29 were then removed from the dataset, and the model parameters were re-estimated with the trimmed dataset.

2.3.2 Experiment 1 Results

Phonological cued recall

The accuracy for the phonological cued recall task was low overall, particularly at T1 (M = .09, SD = .28), as illustrated in Figure 3. However, children's performance improved significantly at subsequent test sessions (T1vsT2: β = 1.01, SE = .15, z = 6.68, p <.001; T2vsT3: β = .86, SE = .11, z = 7.54, p <.001, see Table 1), with the mean proportion of cued recall accuracy being .17 (SD = .37) at T2 and .28 (SD = .45) at T3. There was no influence of semantic conditions, alone or interacting with the test session (ps >.05). Finally, children with higher vocabulary scores demonstrated higher cued recall accuracy (β = .02, SE = .01, z = 2.24, p = .025, see Figure 4), suggesting a general association between existing vocabulary knowledge and cued recall accuracy for new word-forms.

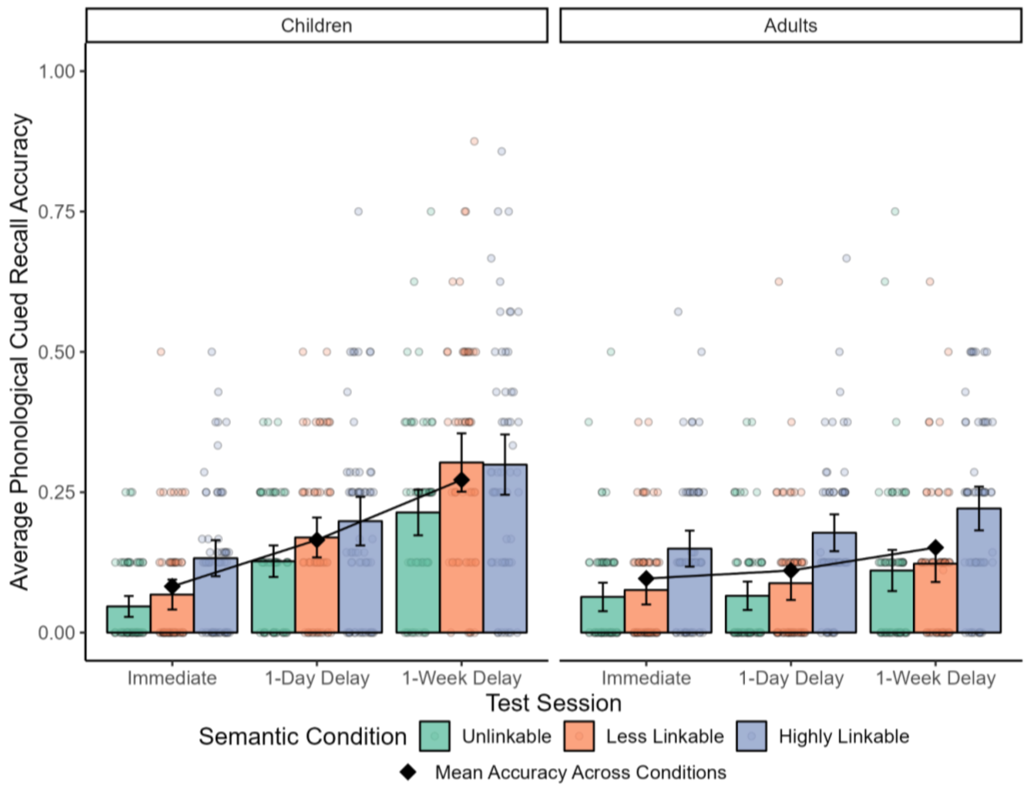


Figure 3 Average phonological cued recall accuracy for each semantic condition for children and adults in Experiments 1 & 2.
Error bars represent 95% confidence intervals, and coloured dots represent participant-level performance

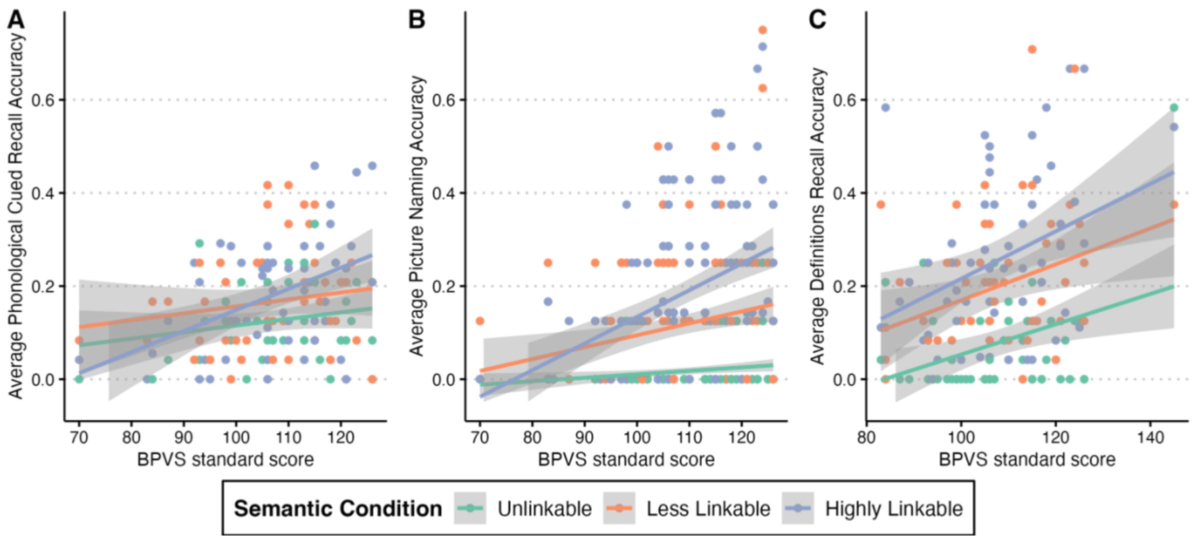


Figure 4 Children's average performance per semantic condition against the British Picture Vocabulary Scale (BPVS) standard scores in the A) Phonological cued recall, B) Picture naming, and C) Definitions recall tasks in Experiment 1.
Grey bands represent 95% confidence intervals.

Table 1 Predictors of Children's Phonological Cued Recall in Experiment 1

Fixed effects	b	SE	z	p	
(Intercept)	-2.30	.25	-9.24	<.001	***
T1vsT2	1.01	.15	6.68	<.001	***
T2vsT3	.86	.11	7.54	<.001	***
Semantics1	-.14	.10	-1.48	.140	
Semantics2	-.09	.26	-.33	.740	
BPVSCentered	.02	.01	2.24	.025	*
T1vsT2:Semantics1	.15	.11	1.28	.199	
T2vsT3:Semantics1	-.08	.08	-1.02	.310	
T1vsT2:Semantics2	.31	.17	1.76	.079	
T2vsT3:Semantics2	.03	.14	.21	.831	
T1vsT2:BPVSCentered	.02	.01	1.74	.083	
T2vsT3:BPVSCentered	.01	.01	.74	.459	
Semantics1:BPVSCentered	-.01	.00	-1.20	.229	
Semantics2:BPVSCentered	-.01	.01	-1.80	.072	
T1vsT2:Semantics1:BPVSCentered	.01	.01	.67	.505	
T2vsT3:Semantics1:BPVSCentered	.00	.01	-.29	.775	
T1vsT2:Semantics2:BPVSCentered	.00	.02	.23	.816	
T2vsT3:Semantics2:BPVSCentered	.01	.01	.53	.598	

Random effects	Variance	SD
Participant: (intercept)	.29	.54
Participant: Semantics1 (slope)	.03	.16
Participant: Semantics2 (slope)	.20	.44

Target: (intercept)	1.22	1.11

* p<.05, ** p<.005, *** p<.001

Note: model from 3738 observations collected from 53 participants across 24 items, after removing 8 influential participants

Picture naming

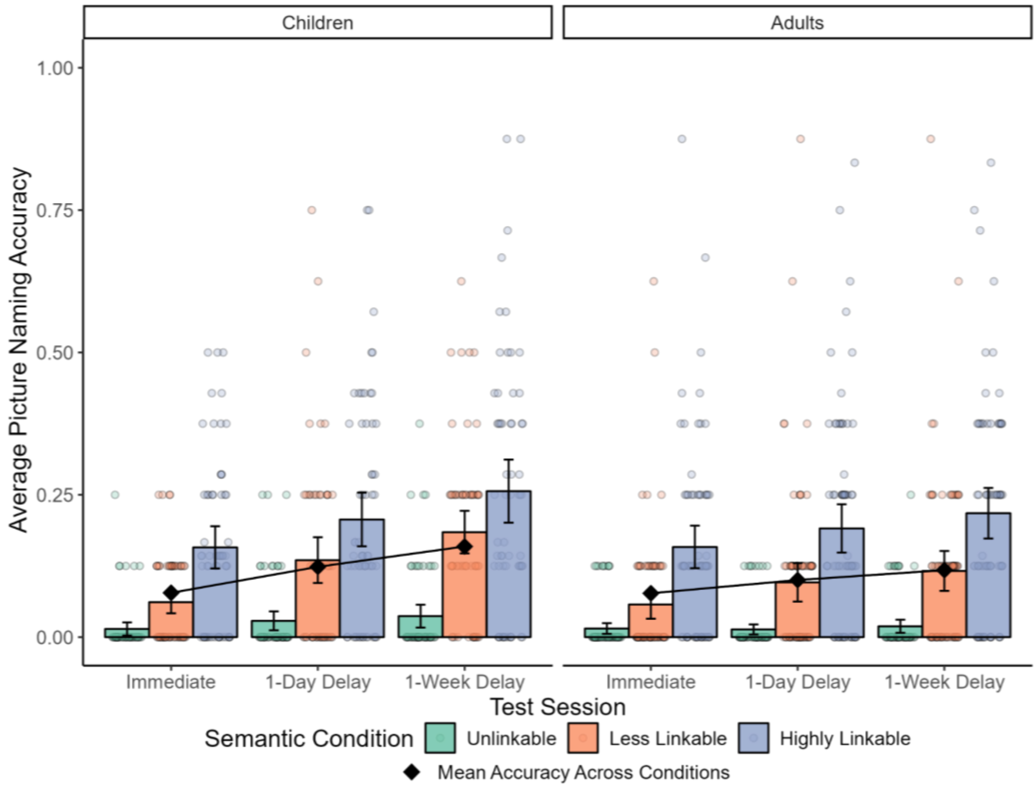


Figure 5 Average picture naming accuracy for each semantic condition of children and adults.
Error bars represent 95% confidence intervals, and coloured dots represent participant-level performance.

Similar to phonological cued recall, picture naming accuracy at T1 was low (M = .08; SD = .27, Figure 5). However, performance improved significantly at the 1-day delay test (M = .12; SD = .33; β = .53, SE = .18, z = 3.02, p = .003), with further improvements at the 1-week delay test (M = .16; SD = .36; β = .52, SE = .15, z = 3.51, p < .001). Again, there was no significant influence from the semantic conditions in picture naming accuracy, either alone or in interaction with test sessions (ps >.13, see Table 2). Receptive vocabulary knowledge was a significant predictor of picture naming accuracy (β = .05, SE = .01, z = 3.76, p < .001). As shown in Figure 4B, children with better vocabulary knowledge showed higher naming accuracy. However, the follow-up analysis suggested that there was no significant interaction between receptive vocabulary and changes across test sessions or with semantic conditions ($ps > .18$).

Table 2 Predictors of Children's Picture Naming in Experiment 1

Fixed effects:	b	SE	z	p	
(Intercept)	-3.03	.29	-10.58	<.001	***
T1vsT2	.53	.18	3.02	.003	**
T2vsT3	.52	.15	3.51	<.001	***
Semantics1	.00	.05	.04	.971	
Semantics2	-.07	.08	-.87	.382	
BPVSCentered	.05	.01	3.76	<.001	***
T1vsT2:Semantics1	.08	.13	.61	.543	
T2vsT3:Semantics1	-.03	.11	-.24	.809	
T1vsT2:Semantics2	-.04	.21	-.20	.839	
T2vsT3:Semantics2	.28	.18	1.53	.126	
T1vsT2:BPVSCentered	.02	.02	1.14	.253	
T2vsT3:BPVSCentered	-.02	.01	-1.34	.181	
Semantics1:BPVSCentered	.00	.00	.98	.327	
Semantics2:BPVSCentered	.00	.01	.15	.881	
T1vsT2:Semantics1:BPVSCentered	-.01	.01	-.88	.379	
T2vsT3:Semantics1:BPVSCentered	.01	.01	.50	.614	
T1vsT2:Semantics2:BPVSCentered	-.02	.02	-1.02	.308	
T2vsT3:Semantics2:BPVSCentered	-.01	.02	-.48	.628	

Random effects	Variance	SD
Participant: (intercept)	.89	.94

Target: (intercept)	1.34	1.16

* p<.05, ** p<.005, *** p<.001

Note: model from 3738 observations collected from 53 participants across 24 items, after removing 6 influential participants

Definition recall

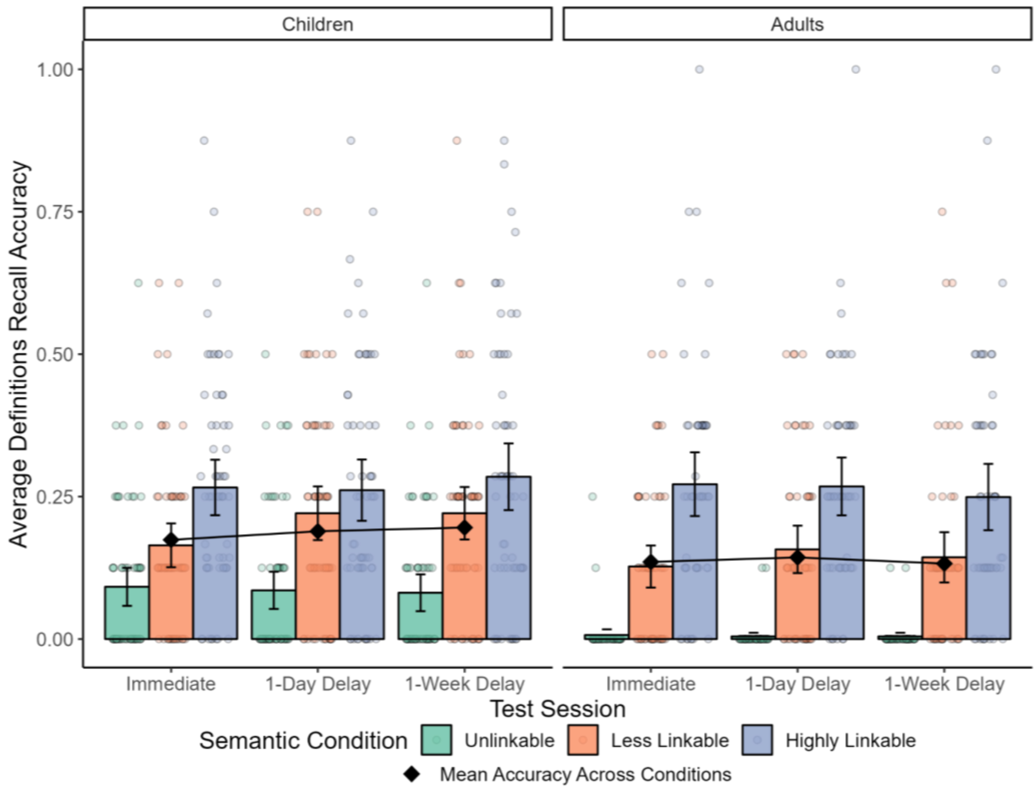


Figure 6 Average definition recall accuracy for each semantic condition in children and adults
Error bars represent 95% confidence intervals, and coloured dots represent participant-level performance

Mean performance in definition recall is shown in Figure 6, summarised across the learning conditions and sessions. Children recalled an average proportion of .17 (SD = .37) of word meanings at the immediate test. Performance remained stable across test sessions (M_{T2} = .18, SD = .38; M_{T3} = .19, SD = .39) and there were no significant improvements across test sessions (ps > .4; see Table 3). Definition recall was significantly better for both types of animals than Unlinkable patterns (β = -.68, SE = .13, z = -5.18, p < .001). However, children showed comparable performance in recalling the meaning of words for Less Linkable (M

= .20, *SD* = .40) and Highly Linkable animals (*M* = .27, *SD* = .44) and there was no significant interaction between test sessions and conditions (*p*s > .15). For individual differences, children with better receptive vocabulary again demonstrated better definition recall overall (β = .04, *SE* = .01, *z* = 4.03, *p* < .001, Figure 4C).

Table 3 Predictors of Children's Definition Recall in Experiment 1

Fixed effects:	b	SE	z	p	
(Intercept)	-2.22	.21	-10.78	<.001	***
T1vsT2	.01	.13	.11	.912	
T2vsT3	.09	.13	.70	.485	
Semantics1	-.68	.13	-5.18	<.001	***
Semantics2	-.21	.19	-1.10	.272	
BPVSCentered	.04	.01	4.03	<.001	***
T1vsT2:Semantics1	-.15	.10	-1.44	.151	
T2vsT3:Semantics1	.00	.11	-.02	.983	
T1vsT2:Semantics2	.16	.13	1.28	.202	
T2vsT3:Semantics2	-.09	.13	-.71	.480	
T1vsT2:BPVSCentered	.01	.01	.91	.363	
T2vsT3:BPVSCentered	.00	.01	.36	.719	
Semantics1:BPVSCentered	.01	.01	.90	.371	
Semantics2:BPVSCentered	.00	.01	-.42	.677	
T1vsT2:Semantics1:BPVSCentered	.00	.01	.56	.578	
T2vsT3:Semantics1:BPVSCentered	.00	.01	-.34	.738	
T1vsT2:Semantics2:BPVSCentered	-.01	.01	-.92	.360	
T2vsT3:Semantics2:BPVSCentered	.00	.01	.22	.825	

Random effects	Variance	SD
Participant: (intercept)	.46	.68

Participant: Semantics1 (slope)	.40	.63
Participant: Semantics2 (slope)	.20	.44
Target: (intercept)	.62	.79

* p<.05, ** p<.005, *** p<.001

Note: model from 4086 observations collected from 58 participants across 24 items, after removing 3 influential participants.

2.3.3 Experiment 1 Discussion

Experiment 1 examined children's learning of new spoken word forms and meanings across three test sessions. Consistent with Hypothesis 1, children showed improvements across repeated tests over the week in recalling word forms when given the first sounds or corresponding pictures as cues. Conversely, meaning recall remained stable across test sessions. This divergent pattern of improvement in word form memory but maintenance of word meaning memory over repeated tests is consistent with previous studies manipulating other dimensions of semantic knowledge. For instance, studies examining the influence of the number of semantic neighbours also showed no consolidation or repeated testing benefits in word meaning recall (James et al., 2023; Tamminen et al., 2013).

The present experiment considered the role of semantic knowledge by examining the impact of individual differences in vocabulary size and manipulating the ease of new word meaning forming links with existing knowledge on new word learning. Across three tasks, we found that existing receptive vocabulary knowledge had a general effect on word learning, such that children with better existing vocabulary recalled more word forms and meanings overall. Contrary to Hypothesis 2, children's performance on the word form recall and picture naming tasks did not benefit from the inclusion of semantic information during learning, regardless of prior knowledge support. One potential explanation for the lack of a difference in learning between Less and Highly Linkable words may be that children lacked the relevant semantic knowledge to support new learning. However, this is unlikely as the Highly Linkable animals were specifically selected to resemble animals that children are familiar with from pilot studies. Furthermore, the definition recall performance showed that children's recall of word meaning *was* more accurate with both Less and Highly Linkable animals, compared to Unlinkable patterns (but with no difference between these two conditions). Thus, rather than not having the existing knowledge to form links with the new words, children's semantic knowledge may not be rich enough to effectively support the learning and/or retrieval of new phonological forms (Mak & Twitchell, 2020). To further explore this possibility, we turn to adults, who have a richer and more complex semantic network and examine the hypothesis that when existing semantic networks are more developed, semantics can make a greater contribution to word learning in Experiment 2.

2.4 Experiment 2 - Adults

Experiment 2 examined semantic benefits in the timecourse of adults' word learning, testing the following pre-registered hypotheses (https://osf.io/w6mvp/):

Consistent with Experiment 1, memory for new word forms should improve across test sessions.

If a general benefit for semantic conditions was found, then items paired with semantic information (i.e. Highly and Less Linkable animals) would be better recalled than items paired with no semantic information (Unlinkable patterns).

There would be better learning of the words paired with semantic information that can be easily linked with existing knowledge (Highly Linkable) than Less Linkable animals. This could manifest either at the immediate test and show less relative improvement from T1 to T2 (following the CLS framework, McClelland, 2013) or, in line with the iOtA model (Lewis & Durrant 2011), which posits that sleep consolidation mechanisms would have greater support the consolidation for schema-consistent items, then we expect an increase in performance from T1 to T2.

2.4.1 Experiment 2 Methods

Participants

We aimed to recruit a comparable sample size as in Experiment 1 (n = 61). The final sample comprised 63 participants (60 females), aged 18 to 23 (M = 19.61 years). They were recruited from the undergraduate and postgraduate student population. All participants were proficient in English with normal or corrected-to-normal vision and hearing. Participants were asked to complete each test session at a similar time on each testing day, but we retained data from all sessions completed on the correct day. Seventy-five participants were recruited, but twelve participants were excluded from the analysis: seven because they completed the 1-day delay test of the experiment beyond one calendar day after the immediate test, four due to technical errors with audio recording and one because of a self-reported history of a developmental disorder.

Design & Procedure

The stimuli and tasks from Experiment 1 were used with some procedural changes: (i) The number of exposures for each novel word was reduced to five from eight exposures in Experiment 1, enabling adults' initial performance on the word form recall task to match children's T1 performance. The number of exposures was determined based on a pilot study conducted with 10 adults. (ii) As opposed to school-based face-to-face testing in Experiment 1, the experiment was delivered online via Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). Participants were instructed to complete the experiment individually in a quiet room using a pair of headphones connected to their computer.

Learning Phase

The same training tasks were used as in Experiment 1. Participants were instructed to repeat each word only once during one round of repetition training, and only one round of picture-word matching was administered.

Testing Phase

In addition to the same word testing tasks used in Experiment 1, adults completed the Stanford Sleepiness Scale (SSS; Hoddes et al., 1972) at the start of each time point to provide a measure of alertness. They also completed the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) at the end of the 1-week delay test for the identification of particularly poor sleep quality. Participants' PSQI total score ranged from 2 to 12 ($M = 6.75$), and this was not correlated with the performance in any of the testing tasks (all rs < .08).

Data analysis

As in Experiment 1, all data were analysed in RStudio (version 2021.09; RStudio Team, 2020) for R (version 3.6.1, RStudio Team, 2020), using the same contrasts for test sessions and semantic conditions. Items for which participants reported prior knowledge were excluded from analyses, resulting in the removal of 6 out of 1536 words, or 0.3% of the data points.

2.4.2 Experiment 2 Results

Phonological cued recall

Phonological cued recall accuracy was low overall and similar to children's performance in Experiment 1 (see Figure 3). Adults recalled a mean proportion of .11 (*SD* = .31) novel word forms at T1, with comparable performance at T2 at .12 (*SD* = .32), which did not significantly differ from each other (p = .25, Table 4). Performance improved significantly at the 1-week delay test with a mean cued recall accuracy of .16 (*SD* = .37, β = .50, *SE* = .13, z = 4.00, p < .001).

Adults recalled word forms paired with pictures of Less and Highly Linkable animals more accurately than word forms paired with Unlinkable Patterns (β = -.36, *SE* = .11, z = -3.15, p = .002). A benefit for Highly Linkable semantic information over Less Linkable semantic information in recalling word form was also found (β = -.60, *SE* = .27, z = -2.23, p = .025), but there was no interaction between test session and semantic conditions (*p*s > .25).

Table 4 Predictors of Adults' Phonological Cued Recall in Experiment 2

Fixed effects	b	SE	z	p	
(Intercept)	-2.85	.27	-10.50	<.001	***
T1vsT2	.16	.14	1.16	.248	
T2vsT3	.50	.13	4.00	<.001	***
Semantics1	-.36	.11	-3.15	.002	**
Semantics2	-.60	.27	-2.23	.025	*
T1vsT2:Semantics1	-.06	.10	-.56	.575	
T2vsT3:Semantics1	.11	.10	1.14	.254	
T1vsT2:Semantics2	-.02	.15	-.15	.883	
T2vsT3:Semantics2	.06	.14	.39	.696	

Random effects	Variance	SD
Participant: (intercept)	.58	.76
Participant: Semantics1 (slope)	.16	.41
Participant: Semantics2 (slope)	.21	.45

Target: (intercept)	1.34	1.16

* p<.05, ** p<.005, *** p<.001

Note: model from 4374 observations collected from 61 participants across 24 items, after removing 2 influential participants

Picture naming

Performance was again low, with adults recalling a mean proportion of .08 (*SD* = .27) of the words correctly at the immediate test (see Figure 5). Picture naming accuracy was comparable at the 1-day delay test (*M* = .09, *SD* = .29; *p* = .41, see Table 5) but improved significantly at the 1-week delay test (*M* = .11, *SD* = .31; *β* = .69, *SE* = .30, *z* = 2.27, *p* = .023).

A significant main effect of semantics was found: adults were more accurate at naming pictures of Less and Highly Linkable animals than naming pictures of Unlinkable patterns (*β* = -1.60, *SE* = .38, *z* = -4.17, *p* < .001). Higher naming accuracy was also found for Highly than Less Linkable animals (*β* = -.78, *SE* = .33, *z* = -2.25, *p* = .019). Similar to the results of the phonological cued recall, there was no significant interaction between test sessions and semantic conditions in influencing picture naming performance (See Table 5).

Table 5 Predictors of Adults' Picture Naming in Experiment 2

Fixed effects	b	SE	z	p	
(Intercept)	-4.64	.52	-8.84	<.001	***
T1vsT2	.29	.35	.83	.406	
T2vsT3	.69	.30	2.27	.023	*
Semantics1	-1.60	.38	-4.17	<.001	***
Semantics2	-.78	.33	-2.35	.019	*
T1vsT2:Semantics1	-.15	.34	-.44	.662	
T2vsT3:Semantics1	.40	.29	1.40	.163	
T1vsT2:Semantics2	.29	.19	1.50	.134	
T2vsT3:Semantics2	.12	.17	.70	.485	

Random effects	Variance	SD
Participant: (intercept)	2.38	1.54
Participant: Semantics1 (slope)	.18	.42
Participant: Semantics2 (slope)	.36	.60
Target: (intercept)	1.83	1.35

* p<.05, ** p<.005, *** p<.001

Note: model from 4089 observations collected from 57 participants across 24 items, after removing 5 influential participants

Definition recall

As shown in Figure 6, adults recalled an average of .15 (*SD* = .35) of the word meanings at the immediate test, and their performance was maintained at the 1-day delay test (*M* = .15, *SD* = .36; *p* = .76; see Table 6). Furthermore, there were no significant changes at the 1-week delay test (*M* = .14, *SD* = .35; *p* = .81). Semantic condition predicted word meaning recall with the meaning recall accuracy for words paired with pictures of Less & Highly Linkable animals being higher than the recall of Unlinkable patterns (β = -2.95, *SE* = .76, *z* = -3.88, *p* < .001). Furthermore, Highly Linkable animals were recalled more accurately than Less Linkable (β = -.56, *SE* = .23, *z* = -2.42, *p* = .016). Semantics did not interact with either test session contrast, suggesting that a general benefit from prior knowledge in recalling word meaning was available across all test sessions.

Table 6 Predictors of Adults' Definition Recall in Experiment 2

Fixed effects	b	SE	z	p	
(Intercept)	-4.80	.80	-5.97	<.001	***
T1vsT2	-.08	.26	-.31	.756	
T2vsT3	-.07	.28	-.24	.813	
Semantics1	-2.95	.76	-3.88	<.001	***
Semantics2	-.56	.23	-2.42	.016	*

T1vsT2:Semantics1	-.22	.25	-.89	.375
T2vsT3:Semantics1	.03	.27	.12	.902
T1vsT2:Semantics2	.18	.14	1.33	.184
T2vsT3:Semantics2	-.01	.14	-.09	.930

Random effects	Variance	SD
Participant: (intercept)	4.56	2.14
Participant: Semantics1 (slope)	2.80	1.67
Participant: Semantics2 (slope)	.26	.51
Target: (intercept)	.91	.95

* p<.05, ** p<.005, *** p<.001

Note: model from 4085 observations collected from 57 participants across 24 items, after removing 5 influential participants

2.4.3 Experiment 2 Discussion

Experiment 2 examined the influence of semantics on word learning in adults. Inconsistent with Hypothesis 1, which predicted improvements in performance across each test session, adults demonstrated maintenance of performance between immediate and 1-day delay tests. Improvements in accuracy were observed only after a longer period of consolidation at the 1-week delay test for the tasks requiring new word form retrieval (phonological cued recall and picture naming). Potentially, adults profited from the additional test retrieval opportunity after a 1-day delay to stabilise their memory traces for further consolidation over sleep. Nonetheless, a maintenance effect was found for the definitions task across the immediate to the 1-day delay tests and also after a 1-week delay at T3.

Consistent with Hypothesis 2, semantic benefits were demonstrated in adults' learning of novel word forms, such that both phonological cued recall and picture naming accuracy were higher in the two semantic conditions than in the Unlinkable condition. Similarly, adults' recall of word meaning was more accurate for words in the two semantic conditions (compared to the Unlinkable). For Hypothesis 3, we found a benefit of recalling word forms that were consistent with existing knowledge, such that there was a general benefit for highly linkable over less linkable semantic conditions. However, contrary to the prediction based on the iOtA framework, this benefit was observed at the immediate test.

2.5 Experiments 1 and 2 Child-Adult Comparison

Experiments 1 and 2 revealed different patterns of results in children and adults despite comparable levels of initial performance. While children showed greater improvements across test sessions, both after a 1-day delay and across the week, greater semantic benefits were found in adults. Children's greater offline consolidation capacity has been demonstrated in previous form recall tasks following new word learning (James et al., 2019; 2023). Specifically, while adults retain greater prior knowledge-dependence across test sessions, children have shown initial prior knowledge benefits that are then superseded by offline consolidation for words with less prior knowledge support (James et al., 2019) or they have not benefited from semantics in word form learning (James et al., 2023). Following these previous studies, we tested two pre-registered hypotheses for cross-experiment comparisons in the word form recall task[1] between adults and children: (i) Children would demonstrate greater improvements from day 1 to day 2 than adults in their phonological cued recall performance. (ii) Adults would receive greater benefit from semantic information, such that their recall of words paired with more semantic information would be better than that of children.

2.5.1 Experiments 1 and 2 cross-experiment analyses

The same test session and semantic condition contrasts were set as in previous analyses, with an additional factor of Group, which compared children in Experiment 1 and adults in Experiment 2. Items excluded in previous analyses due to prior knowledge were also removed from the current analysis, which accounted for 1.2% of all data points. The full model is presented in Table 7.

[1] For consistency, cross-experimental comparisons of the picture naming and definition recall were also conducted, which were not pre-registered. The comparison for these two tasks showed similar developmental trends as that of the phonological recall task with children performing better than adults. Full results of these comparisons can be found in Appendix C.

The main focus of this analysis was developmental differences between adults and children. Overall, children performed better than adults (*β* = -.24, *SE* = .07, *z* = 3.27*, p* = .001). This is due to children showing greater improvements than adults at the 1-day delay test (*β* = -.42, *SE* = .10, *z* = -4.40*, p* < .001), while adults' performance showed improvement after the 1-week delay (*β* = -.16*, SE* = .08*, z* = -1.95*, p* = .051). Post-hoc comparisons showed that, as per our manipulation of reduced exposure, adults and children had comparable performance at the immediate test *(p* = .36), but children showed greater improvements across consolidation opportunities than adults (T1 vs T2: *β* = -.66, *SE* = .18, *z* = -3.70*, p* < .001; T2 vs T3: *β* = -.97*, SE* = .17*, z* = -5.87*, p* < .001).

Furthermore, there was a significant interaction between group and Semantics2 (Less vs Highly Linkable: *β* = -.13, *SE* = .06*, z* = -2.19*, p* = .028). Post-hoc analysis suggests children outperformed adults in both the Unlinkable *(β* = -.56*, SE* = .22*, z* = -2.51*, p* = .012) and the Less Linkable conditions (*β* = -.71*, SE* = .21*, z* = -3.45*, p* < .001), but the groups showed comparable performance in the Highly Linkable condition (*p*= .33, see Table 7)

To summarise, the cross-experiment comparison showed a greater improvement across test sessions in children than in adults despite matching their initial levels of learning, consistent with existing literature showing enhanced consolidation in children (e.g. James et al., 2019; Wilhelm et al., 2013). While the two age groups showed comparable performance in the Highly Linkable condition, children's memory for words with Less Linkable semantics surpassed that of adults.

Table 7 Predictors of Developmental Differences in Phonological Cued Recall in Experiments 1 & 2

Fixed effects	*b*	SE	*z*	*p*	
(Intercept)	-2.42	.22	-10.81	<.001	***
T1vsT2	.57	.10	6.03	<.001	***
T2vsT3	.63	.08	7.82	<.001	***
Semantics1	-.24	.08	-2.83	.005	**
Semantics2	-.35	.23	-1.50	.133	
Group	-.24	.07	-3.27	.001	**
T1vsT2:Semantics1	.02	.07	.33	.743	

T2vsT3:Semantics1	.03	.06	.55	.581	
T1vsT2:Semantics2	.13	.11	1.22	.221	
T2vsT3:Semantics2	.08	.09	.88	.379	
T1vsT2:Group	-.42	.10	-4.40	<.001	***
T2vsT3:Group	-.16	.08	-1.95	.051	.
Semantics1:Group	-.02	.04	-.48	.628	
Semantics2:Group	-.13	.06	-2.19	.028	*
T1vsT2:Semantics1:Group	-.08	.07	-1.15	.252	
T2vsT3:Semantics1:Group	.06	.06	.97	.332	
T1vsT2:Semantics2:Group	-.16	.11	-1.51	.132	
T2vsT3:Semantics2:Group	-.04	.09	-.45	.651	

Random effects	Variance	SD
Participant: (intercept)	.48	.69
Participant: Semantics1 (slope)	.07	.26
Participant: Semantics2 (slope)	.20	.45
Target: (intercept)	.48	.69

* p<.05, ** p<.005, *** p<.001

Note: model from 8536 observations collected from 120 participants across 24 items, after removing 4 influential participants

2.6 General Discussion

This study showed that adults and children benefit from different learning mechanisms during word learning: While both adults and children showed offline gains in newly learned word forms across one week, children's improvement exceeded that of adults after both a 1-day and a 1-week delay. Conversely, adults' recall of word form and meaning benefited from the inclusion of semantic information during learning, especially when direct links with prior knowledge could be formed. Despite the general benefit of learning new words with semantic information compared to no semantics in meaning recall, children did not benefit more strongly from semantic associations when recalling phonological forms. Instead, children with better receptive vocabulary showed overall form-learning benefits. Contrary to theoretical predictions, words paired with varying levels of semantic links received comparable offline support across test sessions, suggesting that semantic and consolidation processes work as largely separate mechanisms to support word learning, and that both are subject to developmental differences.

2.6.1 Offline gains of new words across one week

Children's word form recall improved continuously from immediate to the first delayed test after a 1-day delay, with further improvement at the one-week test, consistent with previous experiments (e.g. Henderson et al., 2013). Adults showed smaller improvements, as their word form recall only showed improvements at the one-week test. The behavioural improvements in both adults and children are consistent with the CLS framework and previous sleep research, which suggests that offline hippocampal reactivation opportunities during sleep between test sessions contribute to the strengthening of word form memory (Davis & Gaskell, 2009; James et al., 2017). However, these improvements are also likely to be partly due to repeated testing. Notwithstanding, previous studies showed that significant improvements in word form recall are only found after repeated testing if sleep occurs between tests, but not over an equivalent length of daytime wakefulness (Dumay & Gaskell, 2007; Henderson et al., 2012). Nevertheless, the design of the present experiment did not allow us to dissociate the relative contribution from repeated testing and offline reactivation during sleep in enhancing the representations of new words.

When directly examining developmental differences in the changes across test sessions, we found that children's offline gains in word form recall were more robust than those of adults. Developmental difference was found even when both groups showed improvements at the end of the 1-week delay, consistent with previous research adopting a similar testing schedule (James et al., 2021, 2023). The differences in memory improvement following delays encompassing sleep consolidation opportunities are consistent with developmental changes in associated sleep parameters (e.g., slow wave oscillations), which contribute to active systems consolidation (Ohayon et al., 2004; van Rijn et al., 2023). As these SWS parameters are relevant to the transfer of new information from hippocampal to long-term neocortical storage, these developmental changes have been proposed to underlie the differences found in behavioural measures (James et al., 2017). Therefore, greater improvements in word form recall seen in children could be supported by more robust cortical consolidation taking place during interleaving sleep. Aligning with this, a recent study has shown that whilst adults can show steeper gains in new word form recall over repeated tests within a single day, children show steeper gains over sleep (Olsson, 2022). Thus, we deem repeated testing to be a less likely explanation of our findings. Furthermore, another recent study also showed greater memory benefits following a nap in children than adults, but the size of this benefit was not correlated with the magnitude of sleep parameters (van Rijn et al., 2023). Potentially, then, children may benefit more than adults from the protection against interference that sleep offers. Further research is needed to fully understand the mechanisms that account for greater consolidation benefits in children and to examine whether the size of the developmental differences in consolidation will hold at different levels of learning. Nevertheless, the continued improvement of word-form memory across the week following learning in both age groups also adds to a growing literature showing that word learning is a gradual process (Gordon et al., 2022), with potential roles for sleep-related consolidation processes and repeated testing opportunities that differ across development.

Contrary to the hypothesis and word form recall task results, definition recall performance showed a maintenance effect rather than improvement across test sessions. Similar results were demonstrated in a recent study with adults and children, whose memory for new word forms improved after a 1-day delay, but memory for new word meanings remained stable across test sessions (James et al., 2023). Therefore, performance gains across multiple retrieval opportunities are more robust for word forms than for word meanings, perhaps due to different mechanisms underlying the encoding and storage of lexical forms and semantic knowledge. Presently, it is unclear whether lexical and semantic knowledge undergoes the same processes of consolidation and incorporation into long-term storage systems, and the present results underscore the need to address this.

2.6.2 Semantic influences in word learning

Children's and adults' word learning differed in terms of the role of semantic influence. Adults showed word learning benefits in the presence of semantic information over non-semantic patterns, with further benefits for semantic information that is highly linkable to prior knowledge. This is consistent with prior research showing that the presence of familiar semantic information benefits word learning (Havas et al., 2018).

On the contrary, no strong evidence for semantic influence was found in children's learning of word forms. Past research investigating children's use of semantics in word learning and retention yields mixed findings. For instance, children who learned new words with meaning showed better form recall than children who only learned the word forms after a 1-week delay, but not in earlier test sessions (Henderson et al., 2013). Yet, children also show initial lexical benefits from orthographic neighbours, which could reflect broader lexical, phonological and semantic prior knowledge (James et al., 2019). However, when learning words with different numbers of overlapping connections in existing semantic networks, children did not show word form benefits for either dense or sparse semantic networks (James et al., 2023). As the current study compared the ease of linking new and existing semantic information, our design was more analogous to that of James et al. (2023), whose results are consistent with the current findings. Potentially, children may be less likely to use semantics to support word form acquisition, relative to their capacity to draw on other forms of prior knowledge, such as orthography and phonology. The present results also extend the scope of these prior findings by manipulating the availability of prior knowledge, from access to the density of existing semantic network connections (James et al., 2023) or variations within the lexicon (James et al., 2019) to the addition of new semantic knowledge with different amounts of prior semantic support.

Contrary to our initial predictions, developmental comparisons suggest that while adults and children showed comparable recall of word forms that are consistent with prior semantic knowledge, children have a better memory than adults for words that have less semantic support. Adults showed a higher dependence on prior knowledge specifically relevant to the items and a smaller role in learning with semantic information in general, compared to no semantic support. Semantic benefits from existing knowledge were observed immediately after learning and maintained across a week, consistent with the CLS framework (McClelland, 2013). This contrasts with children's word form recall, which showed comparable performance across the three semantic conditions, perhaps indicating less reliance on semantic support from existing knowledge and greater reliance on declarative memory consolidation processes. When accounting for the effects of age on children, a further exploratory analysis revealed a similar trend of increasing reliance on semantics (see Appendix D) While children across 9 to 11 years of age showed comparable recall for word forms in the Unlinkable semantics conditions, older children showed a greater general semantic benefit than younger children, consistent with the semantic benefits found in adults. This raises a further question of *when* in the language development trajectory learners transition from relying more heavily on memory consolidation processes to supporting their learning with prior knowledge, and whether educational practices can leverage this shift in learning mechanisms when designing learning materials and teaching strategies. Future studies with a broader age range of children, potentially including adolescents as well, can provide a clearer picture of the developmental trajectory, considering the interaction of age, changes in consolidation systems and variabilities in vocabulary and broader language skills. Furthermore, as children benefit from semantics in recalling word meanings, exploring strategies that can allow this benefit to transfer to word form learning presents an important avenue for research and teaching practices.

2.6.3 The timecourse of semantic influence in word learning

This study aimed to examine *when* semantics exerts influence on word learning, with two specific potential theoretical predictions: prior knowledge support emerges immediately after learning, without needing an extended period of consolidation (McClelland, 2013), or prior knowledge benefit emerges through reactivation processes during sleep (Lewis & Durrant, 2011). Adult results are consistent with predictions of the CLS framework, as new word forms paired with semantic information were recalled more accurately immediately after learning, and this benefit was maintained across test sessions. Combined with the absence of interaction with changes across test sessions, we showed that adults use prior knowledge to support new word form acquisition without the need for a period of prolonged consolidation.

The pattern from the children's results is less clear. There were no strong significant effects of semantic conditions, either alone or in combination with changes across test sessions, in the pre-registered analysis with receptive vocabulary as a predictor of performance. However, the exploratory analyses with nonword repetition and age show a greater overnight improvement for words in the Less Linkable condition than the Highly

Linkable condition (Appendix B). This is consistent with the CLS account, with more rapid acquisition of prior knowledge supporting the rapid acquisition of novel words paired with Highly Linkable animals, while words paired with Less Linkable animals rely more on the gradual transferral of new memories from the hippocampus to the neocortical long-term storage and benefit from sleep. As this is a small effect found in exploratory analyses, and close to the inference level in the analysis with receptive vocabulary, our data is unable to provide definitive evidence to thoroughly evaluate this finding concerning the predictions from the CLS framework and the iOtA model. Future studies will benefit from further investigating which aspects of new words are more or less likely to receive support from existing knowledge.

2.6.4 Individual differences in children's language abilities in supporting new learning

Theories and models of word encoding and consolidation emphasise the consistency with existing knowledge or schema as supporting the effective incorporation of new information (McClelland, 2013). Logically, the breadth of existing knowledge in a developing lexicon is a key factor in influencing the success of forming new connections, as broader vocabulary knowledge can provide more support for the establishment of new lexical entries. In the present study, receptive vocabulary, measuring vocabulary breadth, was a significant predictor of children's performance in all three testing tasks, such that children with better receptive vocabulary showed higher accuracy across all test sessions. Consistent with previous studies, children with better vocabulary knowledge showed greater recall of new word meanings (Adlof & Patten, 2017) and word forms (James et al., 2019; 2021).

Our exploratory analyses also sought to understand the contribution of general language processing and phonological memory capacity to word learning by measuring nonword repetition performance. Akin to the results for receptive vocabulary, nonword repetition scores were also a significant predictor of overall performance in all three tasks (Appendix B). Thus, a better capacity to maintain phonemes in short-term memory may foster a more efficient establishment of new representations. Furthermore, children with better nonword repetition performance show greater overnight improvements in phonological cued recall. Past studies into word learning in individuals with phonological memory weaknesses point towards poor nonword repetition performance as an indicator of less effective phonological encoding, thus limiting new words that were subsequently stored and consolidated (Bishop et al., 2012). Here, with typically developing children, we show that having good phonological processing skills provides a general benefit for learning new words and allows for more efficient overnight consolidation. This highlights the importance of not only understanding the most beneficial timescale for word learning but also understanding to whom it may be the most beneficial.

2.7 Conclusion

This study builds upon previous research and theoretical frameworks of learning and memory, examining developmental differences in the benefits of consolidation mechanisms and prior semantic knowledge in supporting vocabulary acquisition. Critically, we demonstrate a developmental shift in the reliance on underlying mechanisms and processes that support word learning, whilst controlling for initial levels of learning. Directly comparing the memory of new words, children's greater consolidation resulted in better overall learning than adults. Children showed continuous improvements in the recall for newly acquired word forms across a week, regardless of the type of semantic information the words were paired with, with individual differences in global vocabulary and language abilities among children also contributing to the effectiveness of new word form recall. In contrast, the benefits of locally available semantic information, especially semantic information that forms easy association with existing knowledge, were found consistently across test sessions in adults, suggesting that they were more able to utilise the semantic information available at encoding. This pattern of results is partially consistent with the CLS framework that prior knowledge-consistent information can be integrated directly, such that a graded semantic benefit was observed in adults' word learning across semantic conditions. However, the present results did not show greater consolidation across time for less consistent items with existing knowledge, as suggested by the need for repeated hippocampal reactivations and a prolonged consolidation period. Therefore, the present evidence suggests that not only is it important to establish the timecourse and mechanisms of semantic contributions to word learning across the lifespan, but it is also crucial to identify individual differences to understand *whom* this semantic information benefits.

Chapter 3 A Change is as Good as a Rest: No benefits of wakeful rest for novel word learning in children and adults in a classroom-based study

The data files and scripts for the pre-registered and exploratory analyses can be found at https://osf.io/f4xmy. Pre-registrations can be found at https://osf.io/3wtak/.

3.1 Abstract

Prior studies suggest that wakeful rest, a period of quiet rest with reduced sensory stimulation, provides optimal conditions for memory consolidation compared to an equivalent period spent engaging in other tasks; however, it is unclear if the size of its beneficial changes with the development of memory system, or whether children's bigger retention gains than adults over sleep consolidation extend to wakeful rest. This study examined children's (9-10 years; Experiment 3) and adults' (Experiment 4) recall of novel words before and after a 10-minute period of post-learning quiet rest and one week later, in a group classroom context. Wakeful rest, where participants rested with their eyes closed, was compared to an active wake condition, where participants completed timed spot-the-difference puzzles. Children and adults showed no difference in word recall between wakeful rest and active wake retention conditions at the post-retention test or one week later. Compared to adults, children showed greater gains in word form recall across one week, regardless of retention condition, whereas adults' performance maintained over tests. These results question the educational translation of the wakeful rest effect and demonstrate the need to examine the boundary conditions. These results also point towards offline consolidation mechanisms over multiple days, driving developmental differences in memory consolidation rather than a greater benefit of daytime rest in children.

3.2 Introduction

Our ability to learn and retain new words is a fundamental skill across the lifespan, with an accumulation of behavioural and neuroimaging research over the last decade suggesting that sleep plays a critical role in the consolidation of new memories (Diekelmann et al., 2009). Notably, both children and adults benefit from consolidation opportunities that include sleep, from a short nap to overnight and across the course of a week (Axelsson et al., 2016; Schimke et al., 2021). There are multiple factors at play during sleep that likely underpin these consolidation benefits: one key factor is the reactivation of newly learned words during NREM sleep, but sleep also provides passive protection for new memory traces against forgetting and interference (Born & Wilhelm, 2012). Consistent with changes in sleep architecture over the course of development (Ohayon et al., 2004), studies demonstrate that developmental differences in the contribution of sleep to word learning and declarative memory, with greater sleep benefits for children than for adults (James et al., 2019, 2023; Peiffer et al., 2020; Wilhelm et al., 2013). However, it is also possible that periods of ‘cognitive downtime’ during wakefulness, during which the hippocampus is unoccupied, can support the stabilisation and consolidation of recently acquired memories (for a review, see Wamsley, 2022). The present study examined whether adults’ and children’s word learning benefits from a short period of wakeful rest when this is implemented in a group classroom context.

3.2.1 Sleep and novel word consolidation

To form an enduring representation for newly encountered words, strengthening the memory traces and integrating with existing lexical knowledge are crucial steps to prevent forgetting or interference by other information (Dumay, 2016; Wixted, 2004). Overnight improvements in memory for new words are consistent with the Complementary Learning Systems framework (Davis & Gaskell, 2009; McClelland et al., 1995), which suggests that while representations of new words are acquired rapidly in the hippocampus, their integration with existing knowledge in the neocortex requires gradual reactivation. In addition to the benefits from sleep, reactivation can also occur through repeated exposure and retrieval practice during wake to enhance memory (Antony et al., 2017; Roediger & Butler, 2011).

Overnight consolidation benefits have been observed in the strengthening and integration of word forms in both children and adults who slept between learning and recall, compared to those who spent the equivalent amount of time in daytime wakefulness (Dumay & Gaskell, 2007; Henderson et al., 2012). Sleep is particularly beneficial to children's memory, who showed a greater improvement in word form recall than adults following consolidation opportunities (James et al., 2019). This developmental difference also extends to semantic association learning, where children showed greater sleep-related benefits than adults for novel object-function associations; however, an equivalent amount of time in daytime wakefulness yielded comparable forgetting in children and adults (Peiffer et al., 2020). Our recent study further showed children's 24-hour consolidation of novel word forms (i.e., the change in novel word recall between an immediate and 24-hr test) was greater than adults' despite matching levels of initial encoding, with this benefit maintained one week later (Lam et al., 2025). These findings demonstrate that offline consolidation may be more beneficial to children than adults, revealing important developmental differences in memory consolidation mechanisms.

These enhanced memory effects in children have been attributed to increased slow-wave sleep (SWS) at this point in development. This is consistent with Active Systems Consolidation theory, which posits that specific sleep parameters, such as slow oscillation and spindles, are the neurophysiological mechanisms which support the reactivation of new information in the hippocampus and neocortex and thereby facilitate the integration of novel information with existing knowledge during sleep (Diekelmann & Born, 2010). Following this, the greater consolidation observed in children compared to adults could reflect developmental changes in sleep architecture. For instance, the proportion of SWS, which is critical to declarative memory consolidation, reaches a peak in later childhood at around 12 years of age and subsequently decreases across adolescence (Hahn et al., 2019; Ohayon et al., 2004).

The beneficial effects of sleep are not restricted to overnight sleep: daytime naps also provide strong memory benefits, which may be related to the high concentration of SWS during naps (L. Kurdziel et al., 2013). A post-encoding nap was shown to be particularly beneficial in more challenging word learning situations, such as when preschool children are synthesising and extracting word meaning across different story contexts. Williams and Horst (2014) found that 3-year-old nappers showed better retention of new words encountered in stories than those who did not nap shortly after a 2.5-hour nap, and these benefits were maintained 24 hours and 7 days later. A post-learning nap also facilitates memory in adults, protecting the memories of recently learned word forms and facilitating integration to existing lexicon (Tamminen et al., 2017). However, the benefit for naps tends to be smaller than for overnight sleep, potentially due to shorter sleep duration and fewer sleep-stage cycles (Lo et al., 2014).

In a direct comparison of children aged 10-12 years and adults, van Rijn et al. (2023) examined novel word learning over a 90-minute nap and found that children's novel word recall benefited more from the nap than adults. Specifically, children showed a slight improvement in word recall while adults showed a slight decline. However, these behavioural changes over the nap were not correlated with the expected sleep parameters, such as spindle density or SWS duration (see Fletcher et al., 2020; F. R. H. Smith et al., 2018; Wilhelm et al., 2008, for evidence of such associations across overnight sleep). Potentially, then, developmental differences in memory retention during consolidation opportunities may not only arise from developmentally attuned sleep architecture.

As well as providing neural oscillations that directly support mechanisms of memory consolidation, sleep may also support memory through minimising demands on encoding, reducing sensory stimulation and interference, allowing for hippocampal reactivation and integration with existing knowledge (Mednick et al., 2011). This interference-free state may be particularly beneficial to children, who are more susceptible to interference than adults following new learning (Fatania & Mercer, 2017). Research demonstrates that while adults can maintain newly learned information despite interference, children benefit from a 48-hour delay period with overnight consolidation opportunities to reduce interference effects (Darby & Sloutsky, 2015). This suggests the importance of an interference-free delay for the transfer of information to long-term knowledge in children, while also highlighting the need to understand the elements and conditions which are particularly beneficial to support memory consolidation.

3.2.2 Wakeful rest: an alternative state supportive of memory consolidation

Both sleep and quiet rest provide a period during which the hippocampus is not engaged in processing novel information and instead can undergo cellular consolidation, which stabilises recently learned word form representations through replay (Mednick et al., 2011; Wamsley, 2022). For example, spontaneous hippocampal place cell activation during immobile rest periods reflected the replay of a previously exposed environment in rodents, suggesting memory reactivation and stabilisation during this period (Karlsson & Frank, 2009). In human participants, applying targeted memory reactivation to awake participants strengthened weakly encoded object-location associations and reduced forgetting (Oudiette et al., 2013). Therefore, alternative states of reduced external engagement, such as wakeful rest, could potentially offer protection from forgetting for newly learned words like those offered in sleep.

Previous studies have claimed that wakeful resting shortly after learning supports consolidation and protects recently learned materials. Dewar et al. (2012) demonstrated better recall for stories after a 10-minute post-encoding rest, compared to completing spot-the-difference puzzles for the same length of time. This superior recall reflects the beneficial environment wakeful rest creates to support memory stabilisation. Furthermore, longer wakeful rest periods comparable to naps have been suggested to carry comparable benefits (S. Y. Wang et al., 2021). Wakeful rest effects appear to persist beyond immediate benefits to memory and extend to better retention one week later (Dewar et al., 2012, 2014; Martini et al., 2019, 2018). These findings demonstrate that wakeful rest provides additional benefits alongside sleep, serving complementary roles in memory consolidation.

It is also important to note, however, that other studies examining wakeful rest have yielded mixed results, highlighting the importance of establishing the boundary conditions under which a wakeful rest benefit may be found. Meta-analyses suggest a small to moderate overall effect for wakeful rest as well as considerable heterogeneity across studies (Humiston et al., 2019; Weng et al., 2025). For example, Humiston et al. (2019) did not find a memory consolidation benefit using behavioural measures when replicating a previous behavioural and electrophysiological study (Brokaw et al., 2016). The authors proposed that this is partly due to individual differences in participants' internal state during wakeful rest and suggested a greater benefit when the mind is truly in a "resting" state, free from spontaneous thoughts or active engagement with external tasks. A subsequent study has also asserted that engaging in interfering tasks is detrimental to memory, regardless of the attention load required for the distracting task (Craig & Greer, 2024), while Martini et al. (2020) suggested that individual differences in working memory capacity could moderate the size of wakeful rest effects after a week. Yet, Varma et al. (2018) also propose that tasks exerting some attentional demands can suppress autobiographical thinking, thus allowing cognitive resources to be redirected to consolidation processes, and resulting in comparable benefits to wakeful rest. Similarly, a recent study showed comparable memory effects in wakeful rest and social media engagement, as the latter serves a similar relaxation role and requires little effortful cognitive processing (Quevedo Pütter & Erdfelder, 2025). This highlights the need to examine the boundaries for conditions that are most conducive to memory consolidation and consider how they map onto everyday lives.

3.2.3 Applying wakeful rest in the classroom

With wakeful rest providing protection to recently encoded memories that potentially lasts for an extended period, it may be a promising strategy to apply in education settings. However, past findings were mainly based on lab-based studies under a well-controlled environment, and caution is warranted in translating these into real-life settings. One critical consideration concerns the efficacy of wakeful rest in a classroom or group setting. Experimental conditions tend to involve calibration of luminance and noise levels in the environment, as well as specific instructions for body posture and eyes open/closed (Weng et al., 2025). For instance, in a study with children aged 10-13 years, wakeful rest was implemented with the experimenter turning off the lights and resting together with each child one-to-one, to minimise activity throughout the rest (Martini et al., 2021). Such one-to-one attention given to children individually may be possible in a home-schooling or private tutoring setting, but it would be more challenging to implement in a classroom. In one exception, children aged 13-14 years encoded lists of highly familiar words in groups of up to 26 and were tested using a free recall task immediately after each encoding phase - before either wakeful resting or problem-solving - and after one week (Martini et al., 2019). A wakeful rest benefit was observed only among children who scored in the bottom third at immediate recall before engaging in wakeful rest. No difference was found in children with higher initial recall performance, suggesting that there may be considerable differences in the memory benefits from wakeful rest, potentially dependent on initial levels of learning. The variabilities in children's classrooms notwithstanding, the wakeful rest literature also lacks studies on small group testing with adults, with only one study examining participants in small groups of up to 5 adults (Humiston et al., 2019). This leaves an empirical gap in the influence of group dynamics on the ease of disengaging from social environments to enter an offline state supportive of memory consolidation. Evaluating the memory benefits of wakeful rest under group conditions and a more varied environment is a useful step towards understanding the feasibility of incorporating quiet breaks throughout the school day to support children's learning and memory retention.

3.2.4 The present study

Two pre-registered experiments examined whether a 10-minute quiet resting period with eyes closed following learning (i.e., wakeful rest) may lead to recall benefits immediately after resting and one week later, compared to a 10-minute period of completing spot-the-difference puzzles (i.e., active wake) in children aged 9 to 10 (Experiment 3) and adults (Experiment 4). We adopted similar procedures to a previous study (Dewar et al., 2014) and selected spot-the-difference puzzles as the active wake task. The spot-the-difference task was chosen as a cognitively engaging comparison condition that demands hippocampal resources otherwise required for memory. This task engages with visual attention processes distinct from word learning; thereby, a wakeful rest benefit would demonstrate that cognitive engagement, rather than direct interference from similar stimuli, can disrupt consolidation processes (Dewar et al., 2014, 2007; Fatania & Mercer, 2017).

Previous wakeful rest studies have typically examined memory for familiar stimuli, such as memory for stories or a list of known words (e.g. Dewar et al., 2012; Martini et al., 2019, 2021), or meaningless nonwords (Dewar et al., 2014). We extend this prior literature to the learning of novel word-picture pairs, allowing us to test this memory aid in the context of vocabulary learning, as a fundamental language skill. Since wakeful rest is proposed to support hippocampal-cortical communication and cellular consolidation (Wamsley, 2019), novel word-picture pairs should benefit from wakeful rest, given that item-memory and associative-binding both rely on the hippocampus (Shing et al., 2008). We also aim to extend the understanding of variabilities in wakeful rest benefit from the effects of individual differences in working memory capacity (Martini et al., 2020) to the role of existing vocabulary, which has shown to be a predictor of overnight consolidation effects (Henderson et al., 2015; James et al., 2017) as wakeful rest may provide opportunities for novel word integration similar to sleep.

The present study also conducted cross-experiment analyses examining developmental differences in the effects of wakeful rest and week-long consolidation on word learning. Other previous studies investigating the benefits of wakeful rest have shown support for memory retention and consolidation in younger and older adults (Brokaw et al., 2016; Dewar et al., 2014; Martini et al., 2018), as well as in children and younger adolescents (aged 6-7, Fatania & Mercer, 2017; aged 10-14, Martini et al., 2019, 2021). However, there is currently very little research that directly examines developmental differences in the effects of wakeful rest. In one exception, Fatania & Mercer (2017) showed developmental differences such that children aged 6-7 years were more susceptible to forgetting when they completed puzzles, compared to when they rested quietly after learning, whereas adults showed comparable performance in both rest and puzzles. This result points to possible developmental differences in consolidation benefits during periods free from cognitive engagement or encoding when the optimal environment is provided. This complements a greater sleep consolidation benefit in children, suggesting that developmental differences in memory consolidation could stem from mechanisms that are shared by wake- and sleep-based consolidation. If so, we should expect a greater quiet rest benefit in older children (aged 9 to 10) than adults, similar to a greater sleep consolidation benefit in children of this age. Furthermore, we aim to extend the examination of this developmental difference over a longer (one week) period, to understand whether any potential benefits and/or age differences of wakeful rest maintain or accumulate across multiple nights of sleep.

Experiment 3 and 4 Hypotheses

Both experiments were pre-registered at osf.io/3wtak, in which children (Experiment 3) and adults (Experiment 4) took part in two group sessions that were one week apart. The initial session consisted of teaching participants 16 novel word-picture pairs and examining their recall of word forms and word-picture correspondences before and after a 10-minute retention period, either in the wakeful rest group or the active wake group, when they completed spot-the-difference puzzles. Longer-term retention was examined in the second session after a one-week delay, which involved the same word recall tasks and an additional word-picture recognition task. In line with previous studies showing wakeful rest benefits, we predicted that, for each age group, a wakeful rest benefit would be found at the post-retention test for both orthographic word form cued recall and picture naming tasks, with the wakeful rest group showing better recall from pre- to post-retention test than the active wake group. We also predicted a wakeful rest benefit at the one-week delay test, which could manifest as a bigger improvement in memory or less forgetting in the wakeful rest group than the active wake group for the recall tasks.

Developmental comparisons were also planned and pre-registered, comparing the consolidation of new words and wakeful rest effects across experiments in the orthographic cued recall and picture naming tasks. Developmental differences in declarative memory consolidation have been observed across different tasks (cued recall, picture-word associations) and time periods (12 hours to one week), with children showing bigger improvements than adults (James et al., 2019, 2023; Lam et al., 2025; Peiffer et al., 2020). Therefore, we expected that children would have a bigger improvement than adults after one week in both word form recall and picture naming tasks. We also predicted that children would show a greater wakeful rest benefit than adults across recall tasks, both at the post-retention test and at the one-week delay test.

We also explored participants' responses in the subjective experience questionnaire to examine if participants in the wakeful rest condition would be more inclined to quietly rehearse the words during the retention period, and whether their rehearsal frequency predicts recall performance. The role of existing vocabulary knowledge was also explored, as previous work has shown that vocabulary knowledge is associated with the overall accuracy of new word learning, as well as the consolidation trajectory of new words (James et al., 2019). The contribution of existing vocabulary knowledge in word learning outcomes is expected in children and adults, but we would also look for whether it interacts with our manipulation of wakeful rest benefit, as well as with changes across test sessions.

3.3 Experiment 3 - Children

3.3.1 Experiment 3 Methods

Participants

The sample size was determined by power analysis based on previous research in wakeful rest with written stimuli (Martini et al., 2019, 2021) and developmental differences in word learning (van Rijn et al., 2023). R packages *pwr* (Champely et al., 2020) and *WebPower* (Zhang et al., 2023) were used to determine that 59 participants would be needed per condition for each age group to achieve 90% power. Thus, we pre-registered (osf.io/3wtak) a sample size of 120 participants for each age group, with 60 participants in the wakeful rest and active wake conditions, respectively.

As recruitment occurred on a whole-class basis to minimise disruption to school schedules and in anticipation of attrition due to school absences, the sample size exceeded the planned target per group. The final analysis included 75 children in the Active Wake group and 82 children in the Wakeful Rest group. One hundred and seventy-three Year 5 children (aged 9-10) across 7 classes from 4 local primary schools in Yorkshire (UK) participated in the study. Sixteen children were excluded from analyses, including those who were unable to complete the post-retention test or those who missed the one-week delay session due to school absences (n = 12). Children in the Wakeful Rest group who did not follow the wakeful rest instructions during the retention period were also excluded from all analyses (n = 4), including children who did not sit still during wakeful rest (e.g. spinning in a chair).

This study was approved by the University of York Psychology Ethics Committee. Fully informed consent was obtained from school headteachers, and study information was provided to parents with the option to opt their child out.

Stimuli and Materials

Stimuli were adopted from a stimulus set that we developed for a previous study; the selected picture stimuli included illustrations of 8 unfamiliar animals and 8 fictitious creatures (see Appendix A for detailed descriptions of stimuli validation).

Sixteen novel word stimuli consisted of 8 real names or parts of the scientific names for the real animals and 8 nonwords used for fictitious creatures. Some of the real animal names were simplified with a more regular spelling to reduce spelling demands (e.g. *pinchaque*, a mountain tapir, was simplified as "*pinchak*"). The words were recorded by a female native English speaker.

Design & Procedure

The experiment was conducted in children's regular classrooms across two sessions that were one week apart. Whole classes of children (mean: 25 children per class, range: 10 - 40) were given a study booklet to complete during the word learning phase and separate testing booklets for each test session. Novel words and pictures of the animals were presented to the whole group via classroom projectors or interactive boards.

In the first session, children started with a learning phase, during which they were exposed to the novel word-picture pair. Memory of new words was examined immediately after learning and after a 10-minute retention period, using two recall tests examining word form and form-picture correspondence. During the retention period, participants engaged in wakeful rest or completed timed spot-the-difference puzzles. Retention conditions were allocated to half of the participating classes, balanced within schools. The post-retention test consisted of the same tasks as the immediate testing phase, as well as a short questionnaire probing their internal thoughts and activities during the retention period. Following a one-week delay, participants' memories of the words were tested using the same word recall tasks and a 3-alternative picture-word matching task. This was followed by an individual differences measure of expressive vocabulary (See Figure 7 for an illustration of the experimental procedure).

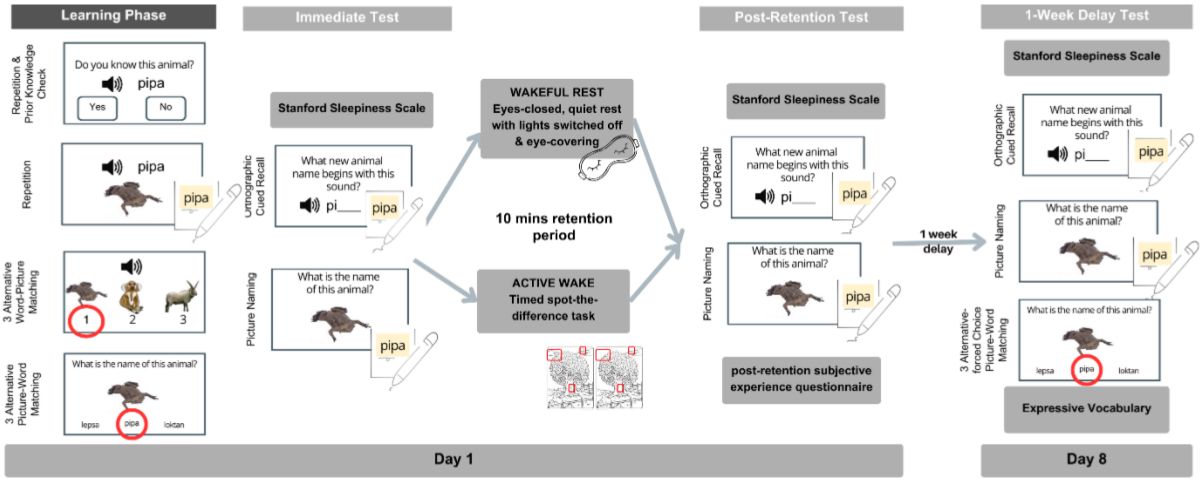


Figure 7 Outline of the study procedure used in Experiments 3 and 4

Retention period

During the retention period, participants in the Wakeful Rest condition were instructed to relax with their eyes closed in their seats. To minimise external stimulation, the classroom lights were switched off, and plain eye coverings were provided. If participants appeared to doze off, the experimenter or the class teacher would give them a light tap on the shoulder as a reminder. Similarly, children were given a light tap on the shoulder if they were making noises or moving excessively. Data from participants who did not engage in wakeful rest were later removed from analysis (n = 4).

Participants in the Active Wake condition completed timed spot-the-difference puzzles during the 10-minute retention period. To increase children's engagement with this task, a 40-second time limit was implemented per puzzle, and they were not told of the number of differences in each puzzle.

At the end of the retention period, all participants were asked to follow some gentle upper-body stretches in their seats. This was to ensure that all children have comparable levels of alertness and that the post-retention recall test was preceded by the same activity (Dewar et al., 2012). Alertness was assessed at the start of each testing phase using the

Stanford Sleepiness Scale (SSS; Hoddes et al., 1972). Children were then informed of the Post-retention Test after they completed the stretches.

At the end of the first session, all participants were asked to complete a short questionnaire of subjective experience and internal activities during the retention period. The questionnaire probed participants' expectations of a post-retention test and the frequency of rehearsing the words, either intentionally or spontaneously, during the retention period. A multiple-choice question was also used to probe whether participants were engaging in different mental activities, such as autobiographical memory ("thinking about the past/future"), meditating or counting the time. Due to time constraints, most children did not complete this portion of the questionnaire; thus, the results for this question were not reported.

Word Learning

In total, participants received 7 exposures to the novel word forms and 6 exposures to the pictures (both excluding distractors in the 3AFC tasks), with 2 opportunities to repeat the word aloud and one opportunity to copy the orthographic forms to their booklet from the screen. Participants learned the written and spoken forms of the novel words across four learning tasks: For the first round of exposure, participants heard and repeated each novel word aloud. Then, they were asked to indicate if they had any prior knowledge of the novel word and, if so, to give a short description of what the animal looked like in their booklet. In the second round of exposure, participants heard and repeated each novel word aloud again. The orthographic form and the corresponding picture were presented on the screen, and participants were asked to copy the words into their booklet.

The next three rounds of presentation took the form of three-alternative multiple-choice questions. In the first word-picture matching task, participants heard one novel word and saw the orthographic form with the corresponding animal picture and two other animals as distractors on the screen. They were asked to indicate the picture that matched the word by circling the corresponding number in their booklet. Feedback was given by providing the correct word-picture pair. The final word learning task involved two rounds of three-alternative multiple-choice picture-word matching. Participants saw one picture and three word choices on the screen. They were asked to indicate the word that matched the picture on screen by circling the answer in their booklet. Feedback was given by providing the correct word-picture pair regardless of response accuracy.

Word Recall Tests

Memories of newly learned word forms and word-picture correspondence were examined with two tasks, orthographic cued recall and picture naming. Participants gave written responses in their booklets. For the orthographic cued recall test, the starting consonant-vowel pairs or triplets for each target word were presented both in written and spoken forms. Participants were asked to recall the rest of the words and to write down as many sounds and letters as they could remember. They were encouraged to make guesses and use alternative spellings if they could recall the sounds of a target word but not the exact spelling.

In the picture naming task, animal pictures were printed on the booklets and participants were asked to write down the names of each animal on the line beneath the picture. Once again, partial answers and guesses were encouraged. Both orthographic cued recall and picture naming were scored by whole-word accuracy (0, 1).

An additional 3-alternative multiple-choice picture-word matching test was added in the one-week delay session to examine participants' recognition. This task was not administered at previous test sessions to avoid providing additional exposure to the correct word forms to children. We included this test at the end of the delay test to examine children's memory of the word-picture association while minimising recall demands. The matching test took place after the two recall tests, using the same procedure as the picture-word matching task in the word-learning phase, except that no feedback was given.

Standardized Assessments

At the start of each word recall test, participants also completed the Stanford Sleepiness Scale (Hoddes et al., 1972), a 7-point scale indicating their state of alertness and sleepiness at the time of testing.

Expressive vocabulary was measured using selected items from the vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence (2nd Ed., WASI-II, Wechsler, 2018). Alternate items from the age-appropriate range were used, and participants were asked to write down a short definition for each word, as opposed to providing an oral definition per the test administration manual. As the vocabulary test was administered in a group context, prompts were not included to request further elaboration on responses. This was completed at the end of the one-week delayed session and was scored according to the test manual.

3.3.2 Experiment 3 Results

The data analysis plan was pre-registered (osf.io/3wtak) and was conducted in RStudio (version 2024.12.1; RStudio Team, 2020), with lme4 (Bates et al., 2025) and emmeans (Lenth et al., 2025) packages to fit mixed models and conduct post-hoc comparisons. Graphs were created using *ggplot2* (Wickham et al., 2024).

As children were recruited from 4 different local schools, orthographic cued recall and picture naming accuracies were compared using Kruskal-Wallis tests, which revealed significant differences across schools (orthographic cued recall: $H(3) = 65.18, p <.001$; picture naming: $H(2) = 18.91, p <.001$). Thus, all pre-registered analyses in Experiment 3 included a nested random effect structure of participants within schools and a random effect of items unless otherwise specified. Items which participants indicated prior knowledge of during word learning were removed from analyses.

Stanford Sleepiness Scale (SSS) scores were compared across retention conditions and test sessions for each age group (children in Experiment 3; adults in Experiment 4) to establish if alertness differed between retention conditions. For children, a 2 (retention conditions) x 3 (test sessions) ANOVA showed SSS scores did not differ significantly between retention conditions ($p = .377$); therefore, SSS scores were not included in the main analyses.

The raw scores of the expressive vocabulary test were compared across retention conditions and schools using a 2 (retention condition) x 4 (schools) ANOVA to decide if it should be included in the main analysis. Results suggest that there was no significant effect of retention conditions ($p = .181$), but performance differs across schools ($F(3, 151) = 5.71, p = .001$). Thus, vocabulary scores were standardised to z scores before being entered into the models as a predictor.

For the main, pre-registered analyses, generalised linear mixed-effects models were fitted for orthographic cued recall, picture naming and picture-word matching tasks separately. Each model consists of the fixed effects of retention condition (AW: Active Wake, WR: Wakeful Rest), test session (immediate test, post-retention test, one-week delay test) and centred vocabulary scores. The 3-level fixed effect of test sessions was coded using repeated contrasts (*Session2-1:* immediate vs post-retention, *Session3-2:* post-retention vs one-week delay).

Orthographic Cued Recall

For the pre-registered model, children from the two retention conditions were matched in their performance at the immediate test (AW: mean = .45, SD = .50; WR: mean = .41, SD = .49, see Figure 8). Contrary to our hypotheses, no effect of retention condition was observed in overall accuracy or in the interaction between retention condition and test session (*ps* > .07, see Table 8). Children's post-retention performance (AW: mean = .44, SD = .50; WR: mean = .39, SD = .49) did not differ significantly from immediate test (*p* = .78) but significant improvement was observed following a one-week delay (AW: mean = .50, SD = .50; WR: mean = .41, SD = .49; β= .31, SE = .13, z = 2.43, p =.015). While vocabulary contributed significantly to overall word learning accuracy (β = .43, SE = .11, z = 3.81, p < .001), its interaction with retention conditions was not significant (*p* = .53).

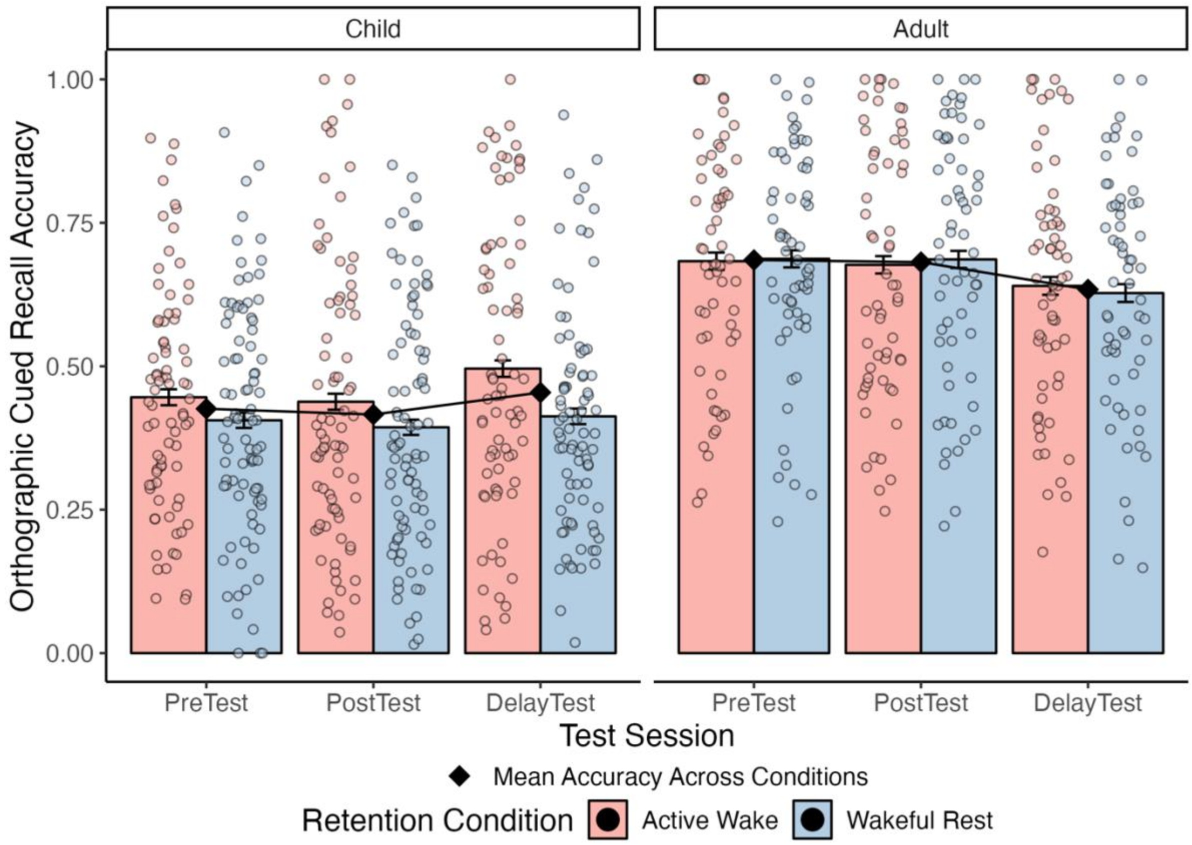


Figure 8 Average orthographic cued recall accuracy by test session and retention condition for each experiment.
The points represent individual performance, and the error bars represent standard error.

Table 8 Predictors of Children's Orthographic Cued Recall Accuracy in Experiment 3

Fixed Effects	Estimate	SE	z	p	
Intercept	-.36	.36	-1.00	.320	
Session2-1	-.04	.14	-.27	.785	
Session3-2	.31	.13	2.43	.015	*
Wakeful Rest Condition	-.31	.17	-1.83	.067	
Vocabulary	.43	.11	3.80	<.001	***
Session2-1:Wakeful Rest Condition	-.03	.14	-.23	.821	
Session3-2:Wakeful Rest Condition	-.17	.14	-1.26	.208	
Session2-1:Vocabulary	.08	.10	.82	.413	
Session3-2:Vocabulary	-.03	.10	-.27	.791	
Vocabulary:Wakeful Rest Condition	-.11	.17	-.63	.529	
Session2-1:Vocabulary:Wakeful Rest Condition	-.11	.14	-.78	.435	
Session3-2:Vocabulary:Wakeful Rest Condition	.07	.14	.48	.629	

Random effects	Variance	SD
Participant:School (intercept)	.89	*.94*
Target: (intercept)	1.01	1.00
Target: (Session2-1)	.14	.37
Target: (Session3-2)	.11	.33
School	.16	.40

Note: Vocabulary – Centred vocabulary scores

Picture Naming

Seven children from the Wakeful Rest condition did not complete the post-retention picture naming test due to time constraints; thus, their data were removed from this analysis. Three additional children were removed from the analysis (2 in Active Wake and 1 in Wakeful Rest) as they did not correctly recall any picture names at the immediate test.

In the pre-registered model, children in the two retention conditions were again matched in their immediate test performance (AW: mean = .36, *SD* = .48; WR: mean = .31, *SD* = .46, see Figure 9). Consistent with the results from the orthographic cued recall test, there was no significant difference between retention conditions ($p = .087$, see Table 9). There were also no significant interactions between retention conditions and test sessions (*p*s > .526). Furthermore, picture naming accuracy did not differ before and after the retention phase and remained stable after the one-week delay (ps > .062), contrary to the orthographic cued recall task. As before, expressive vocabulary significantly predicted overall picture naming accuracy ($\beta = .60$, $SE = .14$, $z = 4.18$, $p < .001$), and there was no significant interaction between vocabulary and retention conditions ($p = .232$).

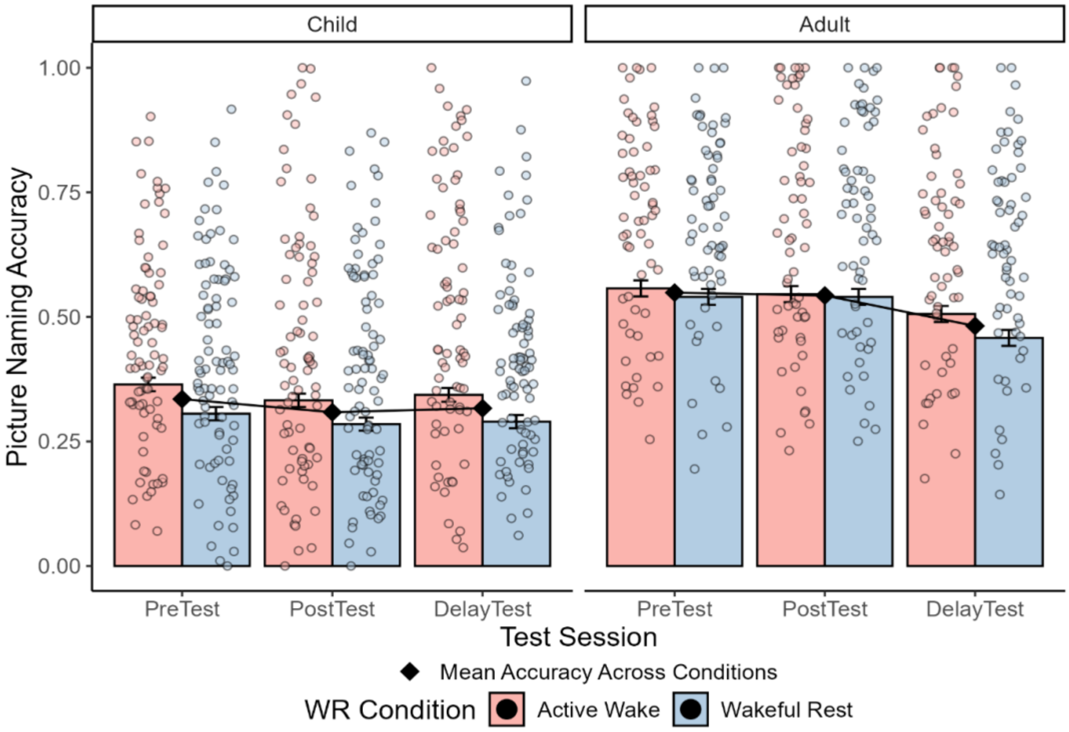


Figure 9 Average picture naming accuracy by test session and retention condition for Experiments 3 and 4
The points represent individual performance and the error bars represent standard error.

Table 9 Predictors of Children's Picture Naming in Experiment 3

Fixed Effects	Estimate	SE	z	p	
Intercept	-.84	.29	-2.92	.003	
Session2-1	-.27	.14	-1.86	.062	
Session3-2	.10	.15	.64	.526	
Wakeful Rest Condition	-.40	.24	-1.71	.087	
Vocabulary	.60	.14	4.18	<.001	***
Session2-1:Wakeful Rest Condition	.10	.15	.64	.522	
Session3-2:Wakeful Rest Condition	.06	.15	.41	.682	
Session2-1:Vocabulary	.06	.11	.60	.548	

Session3-2:Vocabulary	.01	.11	.06	.950
Vocabulary:Wakeful Rest Condition	-.26	.22	-1.19	.232
Session2-1:Vocabulary: Wakeful Rest Condition	.00	.16	.03	.977
Session3-2:Vocabulary: Wakeful Rest Condition	-.25	.16	-1.56	.118

Random effects	Variance	SD
Participant:School (intercept)	1.50	1.23
Target: (intercept)	.84	.91
Target: (Session2-1)	.14	.38
Target: (Session3-2)	.18	.43
Target: (ConditionWR)	.15	.39
School	.02	.13

Note: Vocabulary – Centred vocabulary scores

Picture-Word Matching

Including a nested random effect of participants within schools led to convergence issues, so it was dropped in this analysis, and only the random effects of participants and items were included. Children were significantly above chance level at both rounds of training (TrainingBlock1: mean = .81, *SD* = .40; TrainingBlock2: mean = .88, *SD* = .33, see Figure 10), with significant improvements from Blocks 1 to 2 (β = -.67, *SE* = .16, *z* = 4.13, *p* <.001). However, accuracy decreased following the one-week delay (mean = .81, *SD* = .39; β = .37, *SE* = .19, *z* = 1.97, *p* = .049). Retention condition did not impact overall accuracy or accuracy differences across delays (*p*s > .26). Again, expressive vocabulary predicted overall performance (β = .18, SE = .05, *z* = 3.58, *p* <.001), but not in interaction with other factors (*p*s > 0.29).

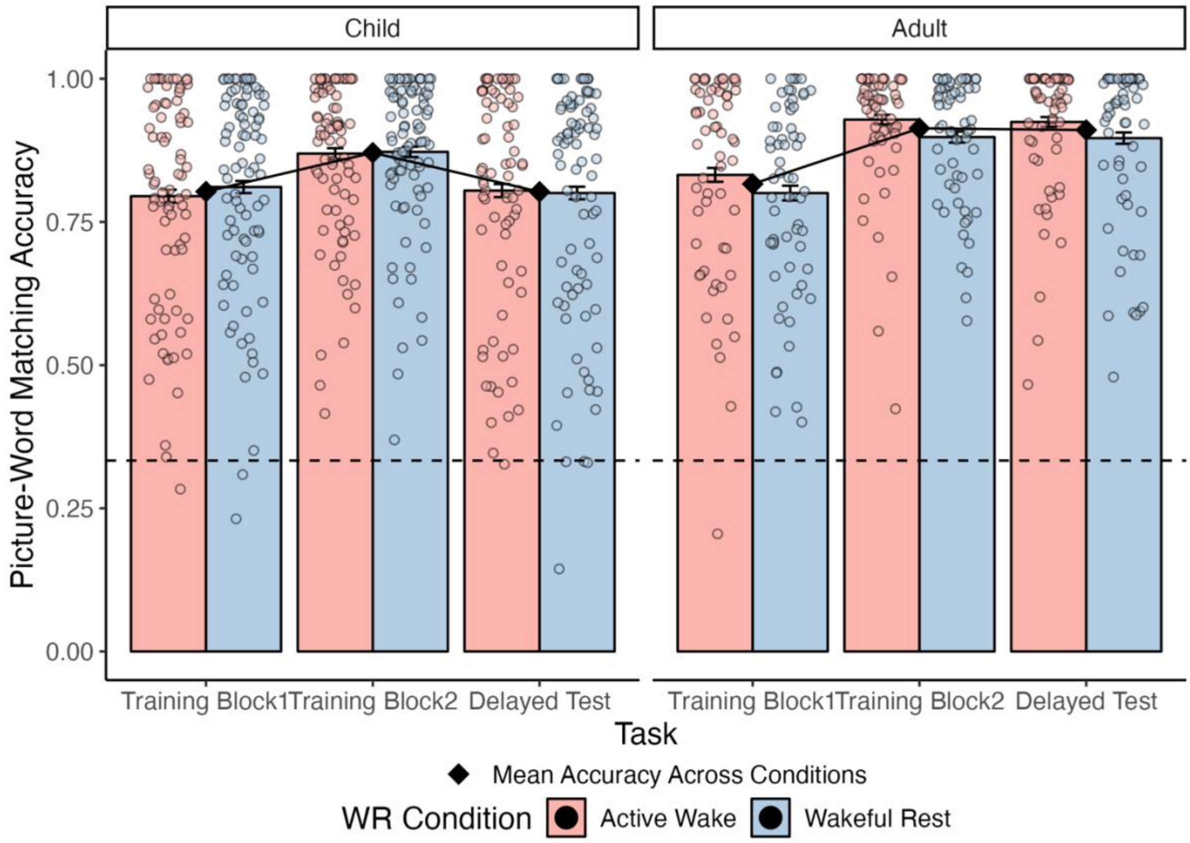


Figure 10 Accuracy in three-alternative forced-choice picture-word matching tasks during training (Training Blocks 1 and 2) and delayed test by each condition for Experiments 3 and 4
The points represent individual performance, error bars represent standard error, and the horizontal dashed line represents chance level (0.33).

Self-reported rehearsal during the retention period

Due to constraints of time and classroom availability, children from 2 of the classes did not complete the self-report questions; only data from 134 participants (64 in AW and 70 in WR) were analysed. As only 4 participants across both conditions reported rehearsing the words “a lot” or “constantly”, these two categories were combined with the previous level, “a few times”. Children’s self-reported rehearsal of the new words was significantly different between the two conditions ($X^2(2, N = 134) = 9.43$, $p = .009$). 25 out of 70 children (35.7%) in the Wakeful Rest group and 38 out of 64 children (59.4%) in the Active Wake group reported thinking about the words at least once during the retention period, contrary to the assumption that wakeful rest provides more rehearsal opportunities than active wake.

3.3.3 Experiment 3 Discussion

Experiment 3 used a between-subjects design to examine the effects of a 10-minute wakeful rest, compared to spending an equivalent amount of time completing spot-the-difference puzzles, on children's memory consolidation of newly learned words immediately after the break and after a one-week delay in the classroom. We hypothesised that there would be better retention in the wakeful rest group than the active wake group in the post-retention test. Yet word recall showed comparable retention in both conditions, and there was no evidence of a greater consolidation benefit for the wakeful rest than the active wake group following the one-week delay, contrary to our second hypothesis. Across all testing timepoints, children in both retention conditions showed comparable performance. On the other hand, a period of offline consolidation strengthened the lexical representations as reflected by children's improvements at the one-week delay test. This suggests that the consolidation benefits for new lexical items observed in previous studies were mainly driven by consolidation processes which took place during sleep, whereas restful breaks during wake are as effective in preserving memory as completing a non-interfering task.

In contrast to the improvement over a week for recall of newly learned word forms, children in both conditions showed either maintenance (picture naming) or forgetting (picture-word matching) for the tasks indexing learning of word form to meaning mapping. This may indicate that overnight consolidation mechanisms primarily benefit the strengthening and recall of lexical word forms, whereas their role in consolidating word-meaning correspondence may be smaller. The selective strengthening of word form may result in increased competition from distractors in the picture-word matching task, resulting in a reduction in accuracy. This is congruent with previous findings showing little to no benefit from overnight and multi-day consolidation opportunities for word meaning recall (James et al., 2023; Lam et al., 2025; Tamminen et al., 2013), thus posing limits to the scope of sleep-driven consolidation mechanisms in word learning.

Consistent with previous studies (James et al., 2023), children's vocabulary ability predicted children's word learning performance across tasks. However, vocabulary ability did not interact with our manipulation of wakeful rest or with changes across test sessions, contrary to the strengthening of lexical representations found across a 24-hour delay in previous studies (Henderson et al., 2015).

Our finding of a lack of wakeful rest contrasts with previous lab-based research, which has shown that wakeful rest benefits declarative memory, such as recall of familiar word lists or stories (Fatania & Mercer, 2017; Martini et al., 2021)[2]. Despite adopting similar wakeful rest procedures and active wake tasks as previous studies, the present experiment deviates from most prior studies as it was conducted in groups, in a classroom setting. Thus, the environment was less controlled than that of individualised testing, especially for the wakeful rest condition. For instance, despite consistent protocols such as switching off the lights and instructing children to stay quiet with their eyes closed throughout the 10-minute rest period, background noises from adjacent classrooms were still unavoidable. Potentially, the confound lies in the noise and stimulation of a school setting, rather than its group nature. To address this potential difference, we conducted a group experiment with adults following the same procedure. Unlike working with children, who are more prone to distraction from peers, the adults completed Experiment 4 in smaller groups and in a quieter room, further reducing the likelihood of external distractions.

3.4 Experiment 4 - Adults

Experiment 4 was a small group-based experiment with adult participants. We examined the same hypotheses as Experiment 3 with children, using the same word recall tests and retention tasks, with a few changes in procedure detailed below.

3.4.1 Experiment 4 Methods

Participants

One hundred and twenty-two adults (aged 18 to 33, 21 males) from the student population participated. All adults were proficient in English and reported no neurodevelopmental disorders relating to language and sleep. Three additional adults were excluded as they missed the one-week delay session. The final sample included 61 participants in each condition.

Procedure

The design was the same as Experiment in smaller groups of up to 14 adults. The experiment took place in a university seminar room, which was located in a quiet corridor in

[2] These non-significant results are substantiated by exploratory post-hoc Bayesian analysis (see Appendix F). Bayes Factor (Orthographic cued recall: $BF_{10} = 0.04$, Picture naming: $BF_{10} = 0.03$) provided strong evidence in favour of the null hypothesis and against a wakeful rest advantage.

the Department of Psychology. Adults were randomly allocated to either the Wakeful Rest or Active Wake condition depending on the session they signed up for, and they received course credits for their participation. The same word learning and testing tasks were used, and adults received the same amount of exposure as children in Experiment 3.

To match the environment as closely as possible to Experiment 3, the retention period was kept at 10 minutes. For the Wakeful Rest condition, the blinds of the seminar were lowered with the lights switched off, and participants were given a black eye covering. In the Active Wake condition, additional spot-the-difference puzzles were included, and a shorter time limit of 30 seconds per puzzle was implemented to keep participants on the task.

Adults also completed the Stanford Sleepiness Scale before each test session and expressive vocabulary at the end of the one-week delay test using selected items from the vocabulary subtest of WASI-II. Same as Experiment 3, expressive vocabulary was administered using a booklet via written responses.

3.4.2 Experiment 4 Results

The same analysis approach as Experiment 3 was used here, except for the random effect structure, which consists of a participant-level and an item-level random effects structure.

A Wilcoxon rank sum test for adults' expressive vocabulary suggested no significant difference in expressive vocabulary between groups ($p = .617$). However, for consistency with Experiment 3, and to explore if changes in recall across test sessions were predicted by vocabulary knowledge, centred expressive vocabulary scores were included in the main analyses.

For differences in alertness between retention conditions, a Wilcoxon rank sum test was conducted for adults' SSS scores due to normality assumption violations. Results revealed no significant difference in SSS scores between conditions ($p = .270$); thus, this was not included in the main analyses.

Orthographic Cued Recall

Orthographic cued recall accuracy was at similar levels for the two retention conditions at the immediate test (AW: mean = .68, SD = .47; WR: mean = .69, SD = .46, see Figure 8). No effect of retention conditions was observed ($p = .962$, see Table 10). Similar to children's performance in Experiment 3, no significant change was observed following the 10-minute retention period (*p* = .481). Performance remained stable across the one-week delay (AW: mean = .64, SD = .48; WR: mean = .63, SD = .48; *p* =.146), contrary to our hypotheses and the findings for children, who showed overall improvement over a week. Furthermore, expressive vocabulary abilities did not predict word form learning in adults (*p* = .18).

Table 10 Predictors of Adults' Orthographic Cued Recall Accuracy in Experiment 4

Fixed Effects	Estimate	SE	z	p	
Intercept	1.03	.32	3.21	.001	***
Session2-1	-.06	.17	-.34	.737	
Session3-2	-.21	.16	-1.36	.173	
Wakeful Rest Condition	.13	.24	.53	.594	
Vocabulary	.27	.22	1.25	.211	
Session2-1:Wakeful Rest Condition	-.02	.18	-.13	.895	
Session3-2:Wakeful Rest Condition	-.10	.17	-.55	.580	
Session2-1:Vocabulary	.05	.16	.32	.753	
Session3-2:Vocabulary	-.14	.16	-.88	.379	
Vocabulary:Wakeful Rest Condition	.14	.28	.50	.618	
Session2-1:Vocabulary: Wakeful Rest Condition	.03	.20	.16	.875	
Session3-2:Vocabulary: Wakeful Rest Condition	.20	.20	.97	.331	

Random effects	Variance	SD

Participant: (intercept)	1.39	1.18
Target: (intercept)	1.16	1.08
Target: (Session2-Session1)	.21	.46
Target: (Session3-Session2)	.13	.36

Note: Vocabulary – Centred vocabulary scores

Picture Naming

Picture naming accuracy was comparable at the immediate test between the two retention conditions (AW: mean = .56, *SD* = .50; WR: mean = .54, *SD* = .50, see Figure 9). Consistent with the orthographic cued recall test, there were no significant main effects or interactions of retention condition (*p*s > .095, see Table 11). Performance after the 10-minute retention period (AW: mean = .55, *SD* = .50; WR: mean = .54, *SD* = .50) was comparable to the immediate test and there was no interaction with the retention condition ($p = .53$). Contrary to orthographic cued recall results and hypothesis, adults' picture naming accuracy decreased significantly across the one-week delay (AW: mean = .51, *SD* = .50; WR: mean = .46, *SD* = .50; $\beta = -.25$, $SE = .11$, $z = -2.20$, $p = .028$). Once again, expressive vocabulary did not significantly predict performance, nor did it interact with other factors (*p*s > .22).

Table 11 Predictors of Adults' Picture Naming Accuracy in Experiment 4

Fixed Effects	Estimate	SE	z	p	
Intercept	.31	.32	.96	.336	
Session2-1	-.07	.11	-.63	.530	
Session3-2	-.25	.11	-2.20	.028	*
Wakeful Rest Condition	-.14	.30	-.49	.625	
Vocabulary	.21	.20	1.08	.279	
Session2-1:Wakeful Rest Condition	.08	.16	.48	.631	
Session3-2:Wakeful Rest Condition	-.27	.16	-1.67	.095	

Session2-1:Vocabulary	-.04	.11	-.32	.751
Session3-2:Vocabulary	-.03	.11	-.28	.779
Vocabulary:Wakeful Rest Condition	.34	.28	1.22	.221
Session2-1:Vocabulary: Wakeful Rest Condition	.13	.16	.82	.414
Session3-2:Vocabulary: Wakeful Rest Condition	-.08	.16	-.52	.606

Random effects	Variance	SD
Participant: (intercept)	2.24	1.50
Target: (intercept)	.98	.99
Target: (Wakeful Rest Condition)	.13	.36

Note: VocabCentred – Centred expressive vocabulary scores

Picture-Word Matching

Adults' performance was above chance from the first block of the 3-alternative picture-word matching task at training (mean = .82, *SD* = .39, see Figure 10), improving significantly in the subsequent training block (mean = .91, *SD* = .28; $\beta = -1.22$, *SE* = .19, $z = -6.47$, $p < .001$). Following the one-week delay, performance levels were maintained (mean = .91, *SD* = .29; $p = .80$). Consistent with the findings for children, retention condition did not result in significant differences in picture-word matching in the following week ($p = .782$). However, unlike previously reported adult results, expressive vocabulary has a general effect in adults' picture-word matching performance ($\beta = .25$, *SE* = .10, $z = 2.51$, $p = .012$), but no significant interaction with retention condition or changes across one week (*p*s > .15).

Self-reported rehearsal during the retention period

As only 1 adult in the WR condition and no adult in the AW condition reported rehearsing the words "a lot" or "constantly", these two categories were combined with the previous level, “a few times”. Retention condition significantly affected the extent to which participants reported they were thinking about the words during the retention period (χ^2(2, N = 121) = 14.78, $p < .001$). Contrary to the self-reported rehearsal by children, more WR participants (68.9%) reported thinking about the words at least once during the retention period, compared to 35% of AW participants.

3.4.3 Experiment 4 Discussion

Adults, akin to the children in Experiment 3, and contrary to our pre-registered hypotheses, showed comparable performance in the Wakeful Rest and Active Wake conditions with no evidence of a wakeful rest benefit[3]. Furthermore, neither of the retention conditions showed significant gains or forgetting between pre- and post-retention tests for the two recall tasks. After a one-week delay, adults’ performance in the orthographic cued recall task was maintained at a comparable level to the previous test. Adults also showed forgetting in the picture-word association task and performed worse in the picture-naming task after one week. This is despite a maintenance in recognising picture-word associations, as indicated by comparable picture-word matching accuracy as the final block of training.

The patterns of recall performance across the one-week delay in adults were different from those of children (Experiment 3), indicating a stronger consolidation mechanism in children across multiple days. Although it should be noted that adults had higher initial performance in both orthographic cued recall and picture naming tasks than children, therefore creating more room for forgetting over long periods of time. To examine whether the pattern of performance for both orthographic cued recall and picture naming tasks was statistically different between the two age groups, the following section compared their accuracy between the two experiments for developmental comparison.

3.5 Experiments 3 and 4 Cross-Experiment Developmental Comparison

The results of Experiments 3 and 4 were consistent in showing no wakeful rest effect for either group. Thus, counter to our pre-registered analysis, we decided not to focus on comparing this null effect but instead to focus on testing whether there was statistical support

[3] Exploratory Bayesian analysis (Appendix F) provided weak evidence against a wakeful rest benefit compared to active wake (Orthographic cued recall: $BF_{10} = 0.95$; Picture Naming: 0.59).

for a developmental difference in retention over the week. Specifically, adults maintained their performance in orthographic cued recall over the week but showed a decline in picture naming recall, whereas children improved their orthographic cued recall and maintained their picture naming recall. Statistical support for this difference would suggest that the dynamics in consolidating lexical entries across a one-week period may differ across development.

Our cross-experiment developmental comparison was pre-registered for the orthographic cued recall and picture naming tasks. Vocabulary was not included as a factor in these analyses, owing to a non-significant vocabulary and retention condition interaction for children and a non-significant effect of vocabulary for adults.

For each of the two recall tests, we fitted a mixed effects model with fixed effects of test session, retention condition and age group (children vs adults) and random effects of participants and targets. The same contrast for the test session was coded as in previous analyses, and this section will focus on the effects of age groups and their interaction.

For the orthographic cued recall test, there was a main effect of age (β = .64, *SE* =.13, z = 4.90, p < .001): adults had better recall than children. Yet, this was in the context of significant interactions of age group with the test session contrast between the post-retention and one-week delay test (β = -.28, *SE* = .08, z = -3.65, p < .001). The interaction of age group with the session contrast between pre- and post-retention tests was not significant (p = .704, see Table 12). As demonstrated in Figure 8, the interaction was driven by children's improvement across the one-week delay (pairwise comparisons: β = .29, *SE* = .13, z = 2.35, p = .049) while adults showed maintenance in performance (β = -.24, *SE* = .12, z = -2.04, p = .103). There was no effect of retention condition, alone or in interaction with other variables.

For picture naming, age group was the only significant main effect (β = .62, *SE* = .14, z = 4.51, p < .001), suggesting adults recalled the picture-word pairings better than children when given the same amount of training, as demonstrated in Figure 9. There was no effect of retention condition or test session, alone or in interaction with other variables (ps > .065, see Table 13).

Table 12 Predictors of Developmental Differences in Orthographic Cued Recall in Experiments 3 & 4

Fixed Effects	Estimate	SE	z	p	
Intercept	.42	.26	1.58	.114	
Session2-1	-.06	.13	-.50	.617	
Session3-2	.05	.12	.42	.672	
Wakeful Rest Condition	-.16	.16	-1.03	.302	
AgeGroup	.64	.13	4.90	<.001	***
Session2-1:Wakeful Rest Condition	.00	.11	.00	1.000	
Session3-2:Wakeful Rest Condition	-.16	.10	-1.52	.129	
Session2-1:AgeGroup	-.03	.08	-.38	.704	
Session3-2:AgeGroup	-.28	.08	-3.65	<.001	***
AgeGroup: Wakeful Rest Condition	.15	.15	1.07	.287	
Session2-1:AgeGroup: Wakeful Rest Condition	.03	.11	.33	.742	
Session3-2:AgeGroup: Wakeful Rest Condition	.02	.11	.19	.848	

Random effects	Variance	SD
Participant (intercept)	1.32	1.15
Target: (intercept)	.93	.97
Target: (Session2-1)	.17	.42
Target: (Session3-2)	.14	.38
Target: (Wakeful Rest Condition)	.06	.24

Target:AgeGroup	.10	.32

Table 13 Predictors of Developmental Differences in Picture Naming in Experiments 3 & 4

Fixed Effects	Estimate	SE	z	p	
Intercept	-.33	.23	-1.39	.166	
Session2-1	-.15	.08	-1.88	.060	
Session3-2	-.11	.09	-1.27	.206	
Wakeful Rest Condition	-.21	.18	-1.18	.240	
AgeGroup	.61	.13	4.91	<.001	***
Session2-1:Wakeful Rest Condition	.07	.11	.66	.508	
Session3-2:Wakeful Rest Condition	-.10	.12	-.81	.417	
Session2-1:AgeGroup	.10	.08	1.22	.223	
Session3-2:AgeGroup	-.16	.09	-1.84	.065	
AgeGroup: Wakeful Rest Condition	.04	.18	.23	.818	
Session2-1:AgeGroup: Wakeful Rest Condition	.03	.11	.33	.742	
Session3-2:AgeGroup: Wakeful Rest Condition	.02	.11	.19	.848	

Random effects	Variance	SD
Participant: (intercept)	1.96	1.40
Target: (intercept)	0.01	0.10
Target: (Session2-Session1)	0.16	0.40
Target: (Session3-Session2)	0.63	0.80

3.6 General Discussion

This study set out to examine whether novel word learning benefits from a short wakeful rest opportunity after learning, focusing on word form recall after a 10-minute retention period and longer-term benefits in recall and recognition after a one-week delay. By adapting wakeful rest procedures from laboratory experiments (Dewar et al., 2012; Martini et al., 2019) to a group context in classrooms, we questioned the extent to which previous laboratory findings can be extended to a naturalistic educational setting. Both Experiments 1 and 2 showed no benefits of wakeful rest in children and adults, either immediately after resting or after a one-week delay, contrary to hypotheses and previous studies showing a wakeful rest benefit. Although adults demonstrated better performance than children overall, improvements over time were only found in children's orthographic cued recall, and only when they had an opportunity to consolidate novel word forms over a one-week period, regardless of the retention condition. In line with previous findings with adults and children (James et al., 2023), developmental differences were only found following opportunities for overnight consolidation after the one-week delay, which lends further support to the notion that the developmental difference in word learning is driven by stronger sleep-based consolidation mechanisms in children, rather than passive protection from interference soon after learning or repeated testing.

Several factors may account for these unexpected findings. The following discussion considers three main areas that may explain the absence of wakeful rest effects in the current study, including participants' internal activities during wakeful rest, our active task choices, and the challenges to implementing wakeful rest in group and classroom contexts. We then turn to developmental differences evident in children's cued recall improvements after one week and consider the implications for theories of memory and consolidation.

3.6.1 Internal activities during wakeful rest

Wakeful rest offers a non-sleep resting state with reduced cognitive demands on encoding and processing; potentially, this disengagement from external stimuli also protects existing memory traces from interference (Wixted, 2004). Beyond that, studies have also suggested that quiet rest may facilitate active consolidation, as similar neural signals observed during slow-wave sleep can also be observed during quiet rest (Brokaw et al., 2016; Mednick et al., 2011; Wamsley, 2019). Specifically, Wamsley (2022) outlined internal activities with high demands of attention or cognitive resources that may prevent wakeful rest, for instance, engaging in recalling events from the past or imagining the future (Craig et al., 2014; Varma et al., 2018) or deliberately focusing on breathing (Richards et al., 2025). Therefore, wakeful rest appears most beneficial when it allows participants to fully disengage from stimulation and preserve cognitive resources for memory processes.

Despite being well-powered to detect a wakeful rest effect between retention conditions based on previously reported studies with children and adolescents, we did not find an effect of rest on word recall. These null findings add to a growing body of research demonstrating variability in wakeful rest outcomes (Richards et al., 2025; Scalia & Wamsley, 2025; Varma et al., 2017). Replication attempts have yielded mixed results, with some failing to reproduce previously reported effects (Humiston et al., 2019). A recent meta-analysis confirmed this heterogeneity of the wakeful rest effect, showing that the size of the wakeful rest effect is modulated by multiple factors, including age, learning type and memory tasks (Weng et al., 2025). This heterogeneity is particularly noteworthy given our study incorporated design features that are associated with small to medium wakeful rest effects reported in Weng et al. (Bowen et al., 2024), such as using a word-based task involving semantics, measuring memory change using a recall task, and adopting a seated eye-closed wakeful rest period under 30 minutes. This suggests that the wakeful rest benefit may be dependent on other environmental or implementation factors beyond study design.

The current study may have prevented participants from achieving the optimal internal state required for wakeful rest benefits, as the procedure was adapted to suit classroom-based settings, departing from the well-controlled environment in previous wakeful rest research. Classroom settings are inherently less well-controlled due to numerous factors, such as students' varying backgrounds and temperaments, as well as differences in classroom culture and facilities (Bowen et al., 2024). In the context of wakeful rest, a noisy and dynamic classroom may prevent children from fully disengaging from the external stimuli and directing their attention inward. For instance, while children were instructed to close their eyes and rest quietly for 10 minutes, activities from adjacent classrooms or corridors may have served as sources of distraction and sensory stimulation. These environmental factors may have interfered with the cognitive disengagement necessary for wakeful rest benefits, keeping participants externally oriented and preventing consolidation. Furthermore, a lack of wakeful rest benefit in Experiment 4 with adults suggests that engaging in wakeful rest within a group may be less effective than doing so in isolation. This is potentially due to increased self-awareness or greater difficulties in disengaging from a social context, which may occupy the cognitive resources that would otherwise be used for memory consolidation. As the wakeful rest benefit is theorised to partially come from the protection of memory traces from interference (Fatania & Mercer, 2017; Wixted, 2004), these further challenge the feasibility of implementing wakeful rest in naturalistic settings.

Prior wakeful rest experiments have used individual testing, with two exceptions in which up to 26 children aged 13-14 were examined in a group in Martini et al. (2019) and up to 5 adults took part in group sessions in Humiston et al. (2019). While a better retention was found following wakeful rest in Martini et al. (2019), this was mainly driven by individual differences in initial learning levels, as pairwise comparisons revealed a significant wakeful rest benefit only among those who scored in the bottom-third at immediate recall. Consistent with the current findings, Humiston et al. (2019) found comparable changes in memory across wakeful rest and distractor conditions. These findings suggest a limit in the robustness of the wakeful rest effect, notably on the efficacy of wakeful rest as an intervention supporting memory retention and consolidation in naturalistic environments (Craig & Greer, 2024; Mercer, 2015). Further experimental and naturalistic work is required to explore the boundary conditions under which consolidation operates during wakefulness, and to develop recommendations that are applicable to classroom demands.

A further limitation of this behavioural approach is the lack of direct insight into participants' internal activities, as the study relied solely on self-reports. Prior research suggests that wakeful rest benefits may depend on underlying neural activity, such as the magnitude of alpha and slow oscillation (Brokaw et al., 2016; Scalia & Wamsley, 2025). It is unclear whether these neural activities occurred during the current behavioural experiment, as the lack of wakeful rest benefit in our study may reflect that participants did not enter the same neural state associated with successful wakeful rest in previous studies. Future studies should consider incorporating online measures of neural activities to directly track neural activities alongside behavioural indicators of wakeful rest.

One possibility is that wakeful rest requires sufficient practice to maximise its benefits (Skaggs, 1933; Wixted, 2004). Skaggs (1933) proposed that well-controlled rest periods should involve participants sinking into a true mental relaxation and quiescence following learning, which could be difficult to attain and could only be maintained for a short period of time. This could be seen in nap studies, where greater memory benefits have been reported for habitual than non-habitual nappers (L. Kurdziel et al., 2013; Leong et al., 2020).

Similarly, studies with mindfulness, which requires sustained focused attention and awareness, also showed that a single session is insufficient to benefit cognitive task performance, and the benefit only emerges after several days of mindfulness training (Johnson et al., 2015; Zeidan et al., 2010). Thus, future studies may benefit from going beyond a single session of wakeful rest and accustom participants to settling in a quiet resting state across multiple periods, before evaluating whether this mental quiescence can benefit memory retention and consolidation.

3.6.2 Minimal interference from the active wake condition

A key factor contributing to the absence of wakeful rest benefits in the current study could be the minimal forgetting effects observed in the active wake group, who engaged in spot-the-difference puzzles during the retention period. We selected spot-the-difference puzzles, which were used successfully in previous studies (Dewar et al., 2012, 2007; Fatania & Mercer, 2017). For instance, Dewar et al. (2012) showed better retention for a list of familiar nouns following a 15-minute wakeful rest, compared to an equivalent amount of time completing timed spot-the-difference puzzles. This active wake task requires sustained attention and cognitive resources that otherwise support the stabilisation of newly learned words. Our self-reported rehearsal question confirmed this, as most of the adults and, to a smaller extent, some children in the active wake group reported not actively rehearsing the words during the puzzles. Yet, minimal forgetting occurred despite rehearsal being prevented, and exploratory analysis also suggested adults' frequency of rehearsal did not predict learning outcome (Appendix E). From an opportunistic consolidation perspective (Mednick et al., 2011), similar memory maintenance suggests that the spot-the-difference task did not strongly interfere with ongoing hippocampal consolidation. This suggests that a wakeful rest benefit may require the contrast with a more demanding active wake condition, such as engaging in further learning or another language-based task (Martini & Sachse, 2020; Varma et al., 2017).

Beyond the characteristics in the active wake task, the strength of initial encoding may also affect the stability of the memory trace. Prior studies on wakeful rest have mostly used familiar word lists or stories and showed participants' reduction in recall or recognition accuracy after the retention period (Brokaw et al., 2016; Tucker et al., 2020). Conversely, our design involved a more extensive encoding paradigm through active repetitions of the orthographic and phonological forms in the learning phase, which might result in stronger memory traces that benefit less from a quiet rest (Schapiro et al., 2018). For instance, the wakeful rest benefit of recalling lists of familiar words in children aged 6 to 7 disappeared when children were given more time to study the list of words, resulting in better initial performance (Fatania & Mercer, 2017). By the final block of picture-word matching training of the current study, both children and adults showed high levels of recognition accuracy (more than 80%), indicating that the memory trace was sufficiently strong, potentially alleviating the need for the protective benefits offered by quiet resting.

3.6.3 Developmental differences in memory consolidation due to sleep

Unlike previous studies of wakeful rest, we did not observe significant forgetting in participants' memory after either retention condition, potentially due to more extensive training and higher initial performance. Rather, children from both retention conditions benefited from a week-long consolidation opportunity such that they showed improvements in orthographic cued recall at the one-week delay test. Instead of attributing the effect to "cognitive downtime" more broadly, the current findings highlight sleep as a mechanism supporting the consolidation and improvement of word form recall over the one-week period. Similar benefits of a delay constituting a sleep period were previously demonstrated in both adults and children from a 12-hour delay (Henderson et al., 2012; Tamminen et al., 2010) to one-day and one-week delays (Axelsson et al., 2016; Clay et al., 2007). Critically, children consistently showed greater improvements in word-form recall than adults following overnight consolidation opportunities, demonstrating developmental differences in memory consolidation mechanisms (James et al., 2019; Peiffer et al., 2020). The present study adds to the understanding of this developmental difference of greater memory consolidation benefits in children than adults by showing that a quiet rest alone does not lead to a greater consolidation benefit in children. Instead, changes in memory happen across a longer period involving overnight consolidation opportunities.

The present results also suggest that repeated exposure and testing are less likely candidates to drive the developmental difference, as a developmental difference was not found in recall accuracy at the post-retention test, following a retrieval opportunity at the pre-retention test. Similarly, Brown et al. (2012) also found comparable recall performance among children before and after a 3- to 4-hour delay within the same day: significant improvements were only found among children whose delay test occurred 24-hour later. Therefore, despite retrieval practice being an effective memory strategy in adults and children (Antony et al., 2017; Goossens et al., 2014; Karpicke & Smith, 2012), it does not appear to account for the stronger one-week improvements seen in children here and in previous studies.

3.7 Conclusion

This study examined whether 'cognitive downtime' in the form of wakeful rest shortly after learning benefits word recall shortly after learning, as well as over a longer period, in adults and children. Despite being adequately powered to detect memory benefits for wakeful rest, the findings did not provide evidence for memory benefits from wakeful rest for newly learned words. Engaging in timed spot-the-difference puzzles for the equivalent duration resulted in similar levels of retention in both the short and longer term. Rather, children benefited from the extended offline consolidation opportunities across multiple days and showed improvements in orthographic word form recall at the one-week test. Since adults showed maintenance in their memory across the same period, cross-experimental comparisons suggest that this developmental difference stems from children benefiting more from offline consolidation mechanisms, rather than from opportunistic protection against interference provided by a short post-learning rest. The findings highlight the need for further studies probing into the boundary conditions that determine when wakeful rest is the most beneficial, considering the interplay of the type of learning and tasks, environmental factors and internal activities during wakeful rest.

Chapter 4 Individual differences in the contribution of semantic prior knowledge and offline consolidation to vocabulary learning in adults with varying literacy skills

The associated OSF project of this study can be found at https://osf.io/j8sfc/; pre-registrations can be found at https://osf.io/qkuy5/

4.1 Abstract

While individual differences in language skills strongly predict word learning outcomes in children, their impact on adults remains underexplored. This study took a dimensional approach, recruiting adults with a wide range of literacy (i.e., decoding and spelling) skills, including adults with dyslexia, to better understand the contribution of semantic prior knowledge to variability in word learning and how this varies across one-week offline consolidation. Adults learned novel spoken words for pictures of real but unfamiliar animals that were highly associated with prior knowledge (e.g., a *pipa*, which resembles a flat frog), or for pictures of fictitious creatures that were less clearly associated with prior knowledge. Adults' ability to recall the new words in response to phonological cues and to pictures was tested immediately after learning and after a one-week delay. Overall, semantics did not support word form recall, as the benefits for words highly-linkable to existing knowledge were only observed in the picture naming task. This suggests that semantic knowledge facilitated only retrieval tasks that specifically draw on semantics and did not strengthen phonological encoding or vary with literacy skills. Adults with poorer literacy skills recalled fewer words immediately and after one week for both tasks. The rate of forgetting over the course of the week was not associated with literacy skills for phonological cue recall. In contrast, literacy skills predicted the rate of forgetting for picture naming, with adults with better literacy skills showing greater forgetting despite better overall performance, potentially due to higher initial performance and greater room for forgetting.

4.2 Introduction

Vocabulary acquisition is a fundamental part of language and literacy development, shaped by both linguistic and broader cognitive processes. Supporting children's vocabulary acquisition has become a priority in education, policy and research (Oxford University Press, 2023), as vocabulary skills intertwine with reading and literacy development across childhood and adolescence (Cain & Oakhill, 2011; Suggate et al., 2018). This priority has been fuelled by nationwide surveys suggesting that literacy gaps persist into adulthood, with up to 18% of adults in England meeting criteria for low literacy proficiency (Wheater et al., 2024). Poor literacy skills in adulthood are associated with lower average wages, higher risk of unemployment and impact social mobility (Kerr, 2021); a report from the National Literacy Trust also suggests that low adult literacy could lead to poorer outcomes in wellbeing, lower family, civic and community engagement, and even lower life expectancy (Teravainen-Goff et al., 2022). These long-term and wide-ranging impacts highlight the need to understand vocabulary mechanisms in adulthood, including factors that facilitate vocabulary learning across the range of adult literacy skills to inform theory and pedagogy.

Drawing on both domain general and lexical theories of word learning, the present study focuses on two key, interrelated factors that support vocabulary acquisition: offline memory consolidation, which supports the establishment of new lexical representations and integration with existing lexicon (Dumay & Gaskell, 2007), and prior semantic knowledge, which allows the formation of a richer representation and promoting integration (Leach & Samuel, 2007). Specifically, the present study examines how the consolidation and retrieval of novel spoken words over one week are influenced by the amount of semantic support from prior knowledge. This study also aims to understand if consolidation and access to prior knowledge benefits varied across adults with a range of literacy skills, following proposals of a greater reliance on semantic knowledge among adults and children at the lower end of the literacy spectrum (Hennessey et al., 2012; Klimovich-Gray et al., 2023). Building on this, we will first consider the support of the broader existing lexical system and language skills (i.e., "global" semantic knowledge), including the contribution of phonological skills and vocabulary as a proxy of semantic knowledge; followed by the support from the inclusion of semantic information specific to new words during learning (i.e., "local" semantic knowledge). Finally, we will turn to the timecourse of this word learning process, and whether the recall of novel words might vary along the spectrum of literacy skills.

4.2.1 Existing linguistic skills supporting novel spoken word learning

Phonological skills

Phonological processing skills, including phonological working memory and phonological awareness (Wagner & Torgesen, 1987), have a lasting impact on how new word representations are established, as initial encoding contributes to the extent to which novel words are successfully consolidated (Wernette & Fenn, 2024). While phonological skills are known predictors of individual differences in reading development (Melby-Lervåg et al., 2012), these skills are also predictors of pre-literacy oral vocabulary knowledge in children at the start of school entry (van Goch et al., 2019). For instance, nonword repetition, which is often used to assess phonological working memory as a proxy for wider phonological skills, is associated with word learning; this association is thought to be mediated by phonological storage capacity (Gathercole, 2006). In an exploratory analysis of our previous study (Chapter 2/Experiment 1), nonword repetition performance predicted school-aged children's overnight improvement in word form recall. One explanation is that children with stronger phonological skills can establish a more defined phonological representation for these new words at the point of encoding, which subsequently benefits to a greater extent from sleep consolidation (Tucker & Fishbein, 2008; Walker et al., 2019). Similarly, nonword repetition predicts the recall and recognition of recently learned word forms in children and adults (Adlof & Patten, 2017; Gupta, 2003). According to the Lexical Quality Hypothesis (Perfetti & Hart, 2002), having high-quality lexical representations, which integrate the phonological, orthographic and semantic components of a word, contributes directly to skilled reading. When poor phonological skills lead to the accumulation of underspecified representations, this also affects the development of accurate phonological-orthographic mappings needed for decoding and literacy development.

The connection between phonological skills and word learning is also clearly evident when phonological skills are compromised, as demonstrated in word learning studies involving individuals with dyslexia. Adults and children with dyslexia experience difficulties in phonological processing, which go beyond phoneme awareness and are reflected in tasks that depend on this system, including verbal short-term memory, nonword repetition, naming and spelling (Snowling, 2005; Swanson & Hsieh, 2009). Weaknesses in phonological processing go beyond poor phonological processing skills increase difficulties in learning new phonological forms, placing additional demands on the learning process (Kalashnikova

& Burnham, 2016). Litt and Nation (2014) showed that children with dyslexia experience more difficulties learning abstract symbol-nonword visual-verbal and nonword-nonword verbal paired associates, but they were unimpaired when the paired associates did not involve a verbal element (i.e. symbol-symbol pairs). Similarly, Kalashnikova & Burnham (2016) found that children with reading difficulties required more training initially to reach criterion when learning novel word-picture pairs and showed poorer recall in a subsequent picture naming task. Combined with neural evidence in children with dyslexia showing an absence of neural enhancement typically associated with early speech sound processing and disambiguation during novel word exposure (Kimppa et al., 2018); existing research evidence points to phonological weaknesses impacting the processing of novel speech sounds and new word encoding, as opposed to an underlying learning deficit more generally. Past studies have suggested that semantic learning is relatively less impacted in adults and children with dyslexia (Bishop & Snowling, 2004; van Rijthoven et al., 2018), but it is less clear to what extent they can leverage prior semantic knowledge to establish new lexical representations as much as adults with better literacy skills and richer vocabularies. It is also unclear whether the offline consolidation of these new representations is also affected by literacy weaknesses, whether directly or indirectly through weaker encoding.

Semantic skills

Another important component supporting word learning is the contribution of prior semantic knowledge (i.e. "global" semantic knowledge). Perfetti et al. (2005) showed that adult skilled comprehenders learned more meanings of rare words within a single session, strongly suggesting that existing vocabulary knowledge promotes the ease of word learning. The lexical restructuring hypothesis (Metsala & Walley, 1998) suggests that greater vocabulary knowledge, a proxy for semantic knowledge, contributes to better phonological awareness, as having more words in the lexicon creates competition that drives more fine-grained phonological representations. This, in turn, facilitates further vocabulary acquisition and supports novel word integration. For children with typical reading, vocabulary skills are a known predictor of spoken and written word learning performance (Adlof & Patten, 2017; Cain et al., 2004; van Viersen et al., 2024; see also Chapter 2/Experiment 1 and Chapter 3/Experiment 3). Similarly, there is evidence that adults' vocabulary could predict word learning outcomes, although the effect of vocabulary is more restricted to incidental learning among a representative sample (e.g. James et al., 2021; but see Chapter 3/ Experiment 4, which did not find an effect of adults' vocabulary when using a university-based sample and an explicit learning paradigm).

The triangle model of reading (Plaut et al., 1996) posits that phonological, semantic and orthographic components of a word work together to support lexical access during reading. This model allows for a division of labour in which the phonological pathway supports the reading of novel words or nonwords, while the semantic pathway is particularly helpful to exceptional word reading (Snowling, 2005; Taylor et al., 2015). Ultimately, both the triangle model of reading and the Lexical Quality Hypothesis emphasise the integration of all three types of representations for spoken and written word processing, which offers the potential of greater reliance on the semantic component when the phonological skills are compromised. Given the relatively preserved semantic ability in adults and children with dyslexia (Bishop & Snowling, 2004), it is possible that semantics may act as a compensatory mechanism to support word learning. This compensatory view is shown in sentence reading by children with dyslexia, who showed greater facilitation from sentence contexts for irregular words than reading-age matched controls, suggesting that children with dyslexia can use semantic cues to supplement their weaker decoding (Nation & Snowling, 1998). Consistent with this, adults with dyslexia who engaged their semantic networks more extensively showed milder reading weaknesses (Klimovich-Gray et al., 2023). Likewise, van der Kleij et al. (2019) found a greater semantic priming effect in children with dyslexia, as semantically related pictorial primes facilitated their word reading more strongly than in non-dyslexic children. This indicates that children with dyslexia show more reliance on direct lexical access through semantic processing, such that semantically related primes have a larger facilitative effect than in non-dyslexic children.

This raises the question of whether individuals with dyslexia can recruit their relative semantic strengths to acquire new lexical phonological representations during word learning. Rasamimanana et al. (2020) examined novel word-picture learning in university students with and without dyslexia and the recruitment of the semantic network to support learning using electroencephalography. Their results presented a mixed picture for semantic compensation: while participants with and without dyslexia both showed good generalisation of novel words to semantically related pictures, participants with dyslexia required more effortful sustained attention during the task. Participants with dyslexia also performed more poorly in the matching task, indicating weaker picture-word association retrieval. Furthermore, whilst previous research suggests that semantic information can help stabilise novel phonological sequences for short-term retention (Savill et al., 2017), Rasamimanana et al. (2020) focused on semantic tasks performance rather than examining phonological form directly. This leaves open questions as to whether learning with semantics may further strengthen phonological encoding during novel word learning in individuals with weaker phonological skills.

4.2.2 Using "local" semantic information to support word learning

The flexible use of semantic and lexical knowledge to learn new words and integrate them into the mental lexicon is important for accumulating knowledge across the life span (Gaskell & Ellis, 2009). Semantic features are central to lexical quality, integrating with phonological and orthographic forms (Perfetti, 2007; Perfetti & Hart, 2002). Therefore, having rich "local" semantic associations allows new lexical representations to be more robust and easily learned. This is demonstrated when consistent local semantic information paired with phonological sequences resulted in more specified phonological representations and supported better immediate auditory discrimination (Hawkins et al., 2015). Phonological representations are better preserved in verbal short-term memory when supported by semantic information (Savill et al., 2017). The Semantic Binding Hypothesis (Patterson et al., 1994) further proposes that semantic information stabilises novel phonological traces in verbal short-term memory by drawing associations with lexical-semantic knowledge, increasing their likelihood of successful encoding. This enhanced encoding provides the foundation for better integration with existing lexical networks. Leach & Samuel (2007) demonstrated that novel words learned with semantic information, such as associated pictures or embedded context, could better engage with existing lexical and sub-lexical phonemic representations. As lexical engagement effects across five days of training, suggesting that semantic information facilitates not only initial encoding but also the formation of connections between new words and existing lexical representations.

The availability of familiar semantic information provides additional support, as it allows closer links to be formed with "global" existing semantic knowledge. When novel words were paired with familiar objects, Havas et al. (2018) showed an enhanced recognition compared to novel words paired with novel objects after a 12-hour delay. This advantage of familiar semantic associations likely reflects the availability of a relevant cluster within the semantic network. When a novel word is paired with a familiar concept, learners can more readily draw on existing semantic associations to support learning. Specifically, preferential attachment suggests that existing concepts that are well-connected in the semantic network are better at supporting the incorporation of new words (Hills et al., 2009; Mak & Twitchell, 2020). In contrast, novel words paired with less familiar semantic concepts require learners to encode both novel phonological and semantic representations, which might increase learning difficulties. These findings demonstrate that providing semantic information enhances word form learning, with familiar semantic association offering particularly strong support. The present study examines how these local connections may vary across adults with diverse "global" literacy skills, testing whether the learning advantage of stronger prior knowledge connections may manifest differently depending on individuals' language skills.

4.2.3 Adding new words to the mental lexicon through offline consolidation

Based on the domain general complementary learning systems (CLS) framework of memory (McClelland et al., 1995), Davis & Gaskell (2009) suggest that newly learned words are integrated with the mental lexicon gradually. Initially, newly learned words are stored in the hippocampus as isolated memory traces which are slowly integrated with other lexical representations distributed across the neocortex either through repeated exposure and retrieval practice (Antony et al., 2017; Roediger & Butler, 2011), or through memory consolidation during offline periods such as sleep or encoding-free periods in wakefulness (Bakker et al., 2015; Dumay & Gaskell, 2007). In line with this, previous word learning studies have shown that recall of novel words is superior following a delay that involves sleep compared to wake (Schimke et al., 2021; Takashima et al., 2017) and following restful wake relative to active wake (Craig & Greer, 2024; Dewar et al., 2014; although see Chapter 3). Specific sleep-based mechanisms have been proposed under the active systems consolidation theories (Klinzing et al., 2016), in which the consolidation for new representations is mainly achieved during slow wave sleep. Word learning studies with polysomnography highlight the association of sleep spindles with the integration of novel words with the mental lexicon during consolidation (Tamminen et al., 2010), whereas the amplitude of slow oscillation was associated with overnight changes in memory performance (Heib et al., 2013).

Individual differences in literacy and vocabulary skills may help to explain the variability in overnight consolidation. James et al. (2017) outlined a sleep consolidation-specific mechanism in which vocabulary knowledge enhances word integration during offline consolidation, as a richer lexical network supports the integration of new lexical items more effectively, thereby fostering vocabulary growth. In a meta-analysis, children with better receptive vocabulary showed a greater overnight increase of the lexical competition effect, which serves as a metric of integration of new lexical representations, among children with better standardised vocabulary performance (James et al., 2017). Conversely, individuals with weaker vocabulary and word learning abilities may be placed at a greater disadvantage. Among adolescents and young adults with a diverse reading and oral language profile, Landi et al. (2018) showed that stronger reading and vocabulary skills predicted greater neural activation for recognising consolidated relative to unconsolidated novel words. The influence of language skills on sleep consolidation is also demonstrated by studies of adults and children with dyslexia. In an overnight consolidation study, Reda et al. (2021) found a lower consolidation rate for unrelated word pairs for children with dyslexia compared to age-matched typical readers. This was despite comparable pre-sleep baseline performance, thus suggesting a smaller contribution of sleep-dependent consolidation to word learning (Reda et al., 2021). This aligns with Smith et al. (2018), who found that children with dyslexia showed comparable levels of consolidation with age-matched controls, yet they exhibited reduced memory gains across a one-week delay relative to younger children matched on immediate recall performance. Furthermore, the role of sleep appeared to be slightly different in children with dyslexia: while slow wave activity was predictive of the memory performance of children in the control group, this relationship was absent in children with dyslexia, suggesting a smaller role for active consolidation. A smaller role of sleep was also found in adults with dyslexia, who showed comparable performance across sleep and wake intervals, in contrast to typical readers who showed significant gains across a delayed sleep interval (Ben-Zion et al., 2023). Taken together, these results suggest a smaller role for sleep consolidation in word learning among adults and children with weaknesses in phonological skills and literacy, potentially modulated by weaker initial encoding.

4.2.4 Consolidation trajectory following semantic learning

Within the CLS framework, McClelland (2013) argues that information that is consistent with prior knowledge can be rapidly learned and directly embedded into neocortical networks without interfering with existing knowledge. In contrast, information inconsistent with prior knowledge requires more gradual integration, in order to avoid interference, and thus there are two different consolidation timeframes for new information depending on their association with existing knowledge. Supporting the prior knowledge advantage, Havas et al. (2018) showed additional semantic benefits for learning novel words with familiar objects than with unfamiliar objects, as recognition was enhanced after 12-hours. However, the familiar semantic benefit appears to operate independently of sleep-based consolidation, as the advantage of familiar objects was observed regardless of whether participants slept or stayed awake during the 12-hour interval. Further evidence demonstrates that semantic associations provide distinct benefits by drawing on prior knowledge, enhancing word recognition and recall prior to sleep consolidation (James et al., 2023; Chapter 2/Experiment 2 of this thesis, though see Schimke et al., 2023, in which no semantic benefit was found and only showed an overall benefit for sleep over wake).

Existing research evidence presents a mixed picture for whether a semantic benefit may persist following consolidation opportunities. An increased semantic advantage over time was also demonstrated, with a bigger recall advantage for novel words paired with pictures after a 1-day delay with adults and with children (Henderson et al., 2013; Takashima et al., 2014). However, a dissociation of semantic support and sleep-based consolidation was demonstrated in Chapter 2 of this thesis. Similar to Havas et al. (2018), adults in Chapter 2/Experiment 2 of this thesis showed a better word form recall for novel words paired with pictures with a stronger link with prior knowledge, than pictures with a weaker link with prior knowledge, regardless of whether recall was tested immediately after learning or one week later. Nevertheless, different manipulations of semantic information could also result in an interference effect rather than a facilitatory role. For instance, James et al. (2023) manipulated the meaning of novel words, either falling into sparser or denser semantic neighbourhoods. Adults, but not children, showed a greater spoken word form recall benefit for novel words paired with concepts within sparser semantic areas immediately and persisted after a 1-week delay period, as there is less interference from related concepts in sparser semantic areas (James et al., 2023). As the evidence outlined in this section is based on adults and children with typical reading and language skills, and given a potentially weaker role of consolidation in individuals with literacy skills, it is unclear how the timecourse of word learning with semantics may differ under weaker consolidation and phonological processing systems.

4.2.5 The Present Study

The current study trained novel word-picture pairs via explicit encoding, which results in stronger declarative memories for novel words (Coutanche & Thompson-Schill, 2014) that can benefit from offline memory consolidation (Diekelmann et al., 2009). Adults learned the phonological forms of 16 novel words paired with pictures of animal referents. To examine whether "local" semantic knowledge facilitates word form learning across adults with a variable profile of literacy and language skills, half of the words were paired with pictures of rare but real animals to prompt participants to form links with their prior knowledge (Highly Linkable), while the other half were paired with pictures of fictitious animals which did not have a clear link with familiar animals (Less Linkable). Furthermore, we also manipulated the time of recall to examine the encoding and consolidation of novel words. Participants' memories of the phonological form and word-meaning association of these novel words were tested immediately after learning and again after a 1-week delay. We assume that performance at the 1-week test benefits from offline consolidation processes. It is certainly possible that the delayed test is also influenced by spontaneous rehearsal as well as retrieval practice during the immediate test, and thus, we cannot determine if there are unique contributions. A battery of vocabulary and language measures was also used to examine the contribution of "global" prior knowledge, in the form of individual differences in literacy skills (nonword decoding and spelling), the depth of general semantic knowledge (expressive vocabulary), and phonological working memory (nonword repetition).

In the original pre-registration (https://osf.io/qkuy5), we planned to use a group comparison approach to examine word learning outcomes in adults with and without dyslexia. However, the recruited sample (see Methods) showed that only a small subset of participants in the dyslexia group met the inclusion reading skills criteria. Thus, we examined individual differences in novel word learning and consolidation in adults with a wide range of literacy skills, adopting a dimensional approach and treating decoding and spelling skills as a continuous measure of literacy (Astle et al., 2022). This approach is consistent with evidence that reading difficulties are driven by multiple risk factors and that phonological and language skills vary along a spectrum (Snowling & Hayiou-Thomas, 2006; Snowling & Hulme, 2012). As orthography is a known weakness among adults with struggling literacy skills, we chose not to include written presentations of the new words during training in this study to prevent confounding orthographic encoding, the examination of word form learning and consolidation abilities (although see Baron et al., 2018, who provided orthography to children with dyslexia to support spoken word learning). We examined whether adults' literacy skills impact novel word learning and consolidation effects across one week, similar to how children's vocabulary skills can modulate gains in consolidation (Henderson et al., 2015; James et al., 2017). Building on evidence that semantic information is particularly beneficial to word processing in individuals with weaker phonological processing (Lukic et al., 2024; Savill et al., 2019), we test whether similar patterns emerge during novel word learning. These findings not only have potential educational impact but also advance theoretical models of word learning by clarifying the relationship between phonological and semantic contributions.

We tested the following hypotheses, which were originally pre-registered for the group comparison, but were later modified for a continuous approach:

- H1. Based on Studies 1 and 2 of this thesis, consolidation of the novel word forms is expected, such that recall accuracy will be maintained or improved following a one-week delay compared to the immediate test.
- H2. Adults with better literacy skills will show more accurate word recall at the immediate test.
- H3. Changes in memory for the newly learned words from the immediate to the 1-week delay test will be predicted by adults' literacy skills, such that adults with better literacy skills will show improvements in recalling novel word forms at the 1-week delay test compared to the immediate test. In contrast, those with poorer literacy skills are expected to show smaller improvements (F. R. H. Smith et al., 2018) or even forgetting (Reda et al., 2021), potentially due to underlying atypical consolidation mechanisms impacting word learning.
- H4. Phonological representations (word form recall) will benefit more from semantic information that can be easily linked to existing knowledge than from semantic information that is harder to form links with, following our previous findings (Chapter 2, Experiment 2). As picture naming directly recruits semantic knowledge during the task, it is expected that the same semantic benefits would be found in this task.
- H5. As an exploratory investigation, we also consider whether semantic benefits differ in participants with different levels of literacy skills. Specifically, we explore if the compensatory effect of semantics previously documented in dyslexia word recognition (van der Kleij et al., 2019) can also support the establishment of new phonological representations.

4.3 Experiment 5 Methods

Participants

Seventy-seven adults (46 females) with varying literacy skills completed two sessions one week apart. All participants were native speakers of English, with 21 participants reporting some knowledge of an additional language. Participants also reported no vision or hearing impairments and had a minimum education level of GCSE or equivalent. The study was approved by the Department of Psychology Ethics Committee at the University of York.

Ninety-one participants were recruited from Prolific (http://www.prolific.com) and received £8 as reimbursement for their time upon experiment completion. Fourteen participants were excluded from analysis, due to failing to complete the 1-week delay session (n = 9), failing both attention checks (see below) within the same session (n = 1), audio recording file corruption (n = 1) and showing prior knowledge of the nonwords at the prior knowledge check suggesting they had participated in a previous study using these stimuli (n = 2). Table 14 contains the demographics and descriptives of standardised language tests of the included participants.

We initially aimed to recruit two groups of 40 adults with and without dyslexia, following sample size calculation as detailed in the pre-registration (https://osf.io/qkuy5). The initial inclusion criteria for the dyslexic group included self-reporting a diagnosis or suspicion of dyslexia and scoring a standard score of 90 or below in two out of three standardised subtests (TOWRE-2 word reading, TOWRE-2 nonword reading and WRAT spelling subtests). Descriptive statistics for background measures for the original groups are provided in Appendix G. However, following extensive recruitment, it became clear that very few participants with dyslexia would meet these criteria (i.e., 7 out of 37 recruited in the dyslexic group). Given that dyslexia is a cumulation of multiple risk factors with additive and interactive effects to impact word learning (Catts & Petscher, 2022; Pennington, 2006), a dimensional approach was taken, with participants from the dyslexic and non-dyslexic groups pooled into a single group. The two most highly correlated measures, nonword reading and spelling (r = .70), were used as a continuous composite measure of literacy skills. This approach allowed us to test the same pre-registered hypotheses by considering effects across the literacy continuum rather than group differences. Based on the effect sizes obtained in the previous experiment (Chapter 2, Experiment 2), 40 participants would be sufficient to detect the effects of test sessions with 80% power. The power curve for semantic contrasts plateaus at around 60% power at around 35 participants.

Table 14 Demographic and language test descriptive statistics of participants in Experiment 5

	Mean (SD)	Range
Age (Years)	27.8 (5.13)	18-35
Adult Reading Questionnaire [1]	14.36 (6.43)	2-28
WASI-II Vocabulary[2]	17.08 (3.69)	5-24
CTOPP-2 Nonword Repetition [2]	18.41 (4.23)	5-27
TOWRE NonWord Decoding [3,4]	100.57 (13.75)	64-126
TOWRE Word Reading [3,4]	97.63 (12.04)	64-127
WRAT Spelling Subtest [3]	100.64 (14.87)	69-131

Notes: [1] Maximum ARQ score is 43; [2]Due to changes to administration (see "Literacy and Language measures" below), the accuracy for vocabulary and nonword repetition was not converted to standard scores. The maximum score for vocabulary is 28 and for nonword repetition is 30; [3] Standardised Score (Mean = 100, SD = 15), calculated following the scoring manual; [4] Data missing from 1 participant due to recording issues.

Stimuli

The stimulus set consisted of 8 novel words and 8 words derived from the common or scientific names of unfamiliar, real animals, adopted from Experiments 1 and 2 in Chapter 2 (Refer to Appendix A and pp. 41-42 for the full description of the stimuli). Each novel word was paired with an illustration of a fictitious creature (Less Linkable Condition), while the real animal name derivatives were paired with the corresponding animal illustration (Highly Linkable Condition). All words were presented auditorily only and were recorded by a female British English speaker.

Design

Semantics were manipulated using pictures of either a fictitious creature for the Less Linkable Condition or an unfamiliar, real animal in the Highly Linkable condition. The effect of time was manipulated using two testing sessions: immediately after learning and after a 1-week delay. Semantics and test sessions are both fully crossed within participants. The majority of participants (73/77 participants) completed the 1-week delay test between 6 and 10 days following the initial learning and testing session; the remaining 4 participants completed up to 14 days following the initial training and test session. As the 1-week delay test performance of these participants was not identified as outliers when compared with those who completed the test according to the planned schedule, the data of these participants were included in the analysis.

Procedure

Given that decoding is one of the core weaknesses of dyslexia, only spoken words were trained and tested in this experiment, with no orthography of the novel words presented at any stage. All spoken novel word stimuli were presented via headphones. Participants were tested online and instructed to complete the experiment in a quiet environment using their personal computer. Tasks were delivered using Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). Participants were told that they were going to learn about the names of some new animals and would be providing verbal responses via audio recording, button press or typed responses. The initial session consisted of a training phase with four word-learning tasks, followed by two word-recall tests. The 1-week delay session consisted of the same two word-recall tests, followed by four standardised measures of vocabulary and language skills.

Literacy and Language Measures

Participants first completed the Adult Reading Questionnaire (Snowling et al., 2012), which measures participants' perceived difficulties related to reading and spelling skills, alongside other demographic questions to capture age, sex, levels of education and second language(s). Following this, the 7-item Stanford Sleepiness Scale (SSS, Hoddes et al., 1972) was administered at both sessions to determine any differences in alertness across the two sessions (of which there were none, $p = .922$). The remaining background measures were administered in a fixed order in test session 2 following word recall tests: Literacy and reading abilities were assessed using the spelling subtest of the Wide Range Achievement Test (WRAT-5, G. S. Wilkinson & Robertson, 2017) and the Test of Word Reading Efficiency, which includes speeded word-reading and nonword-reading subtests (TOWRE-2 Torgesen et al., 2012), with the tasks administered and scored following the test manuals. Language abilities were assessed using a nonword repetition task and an expressive vocabulary task. The nonword repetition task followed the corresponding subtest from the Comprehensive Test of Phonological Processing - Second Edition (CTOPP-2, Wagner et al., 2013), except cut-off rule was applied as no feedback was given to the initial items. The expressive vocabulary task was a definition generation task based on the vocabulary task in the Wechsler Abbreviated Scale of Intelligence (2nd Ed., WASI-II, Wechsler, 2018), with the following changes: alternate items were selected from the full test to reduce the length of the task, participants gave written responses rather than spoken definitions, and no clarification questions were asked following partially correct responses.

Word Learning

Prior knowledge check

As real animal names were used for some of the stimuli in the highly linkable condition, participants were asked if they had any prior knowledge of the animal names. This also allowed us to screen out participants who showed knowledge of the nonwords, which indicated that they might have participated in a previous experiment. All animal names, both in the less and highly linkable conditions, were presented individually through the headphones, and participants were asked to repeat the words out loud and indicate whether they knew these words using a button press. Participants were instructed to report knowing these animals if they had a good idea what the animal looked like and were asked to record a short description (i.e., a definition) to demonstrate their knowledge. Real animal names, of which the descriptions which matched the actual animal were removed at analysis, but we retained the items which participants may have heard of but could not give a clear description of the animal, or if the animal description did not match the stimuli (e.g. describing a bird when the target stimulus is a type of squid).

Repetition

Each animal name was presented with the corresponding animal picture, with the latter remaining on screen for 8 seconds. Participants were asked to repeat the names aloud. Repetitions were audio-recorded and checked to ensure that participants followed task instructions. Participants who did not repeat the words would be excluded.

Word-Picture Matching (3-AFC)

Participants completed two rounds of word-picture matching to promote their learning of the word-picture correspondence. On each trial, an animal name was played through headphones alongside three animal pictures, which included the target animal picture with two distractors, one from each semantic condition. Participants were instructed to click on the picture that matched the name they heard. After each selection, feedback was provided by presenting the correct word-picture pair on screen.

Picture-word matching

The final training task presented an animal name and an animal picture, which matched the target word half of the time. Participants were asked to indicate if the word and picture matched with a button press. The correct word-picture pair was presented after the response.

Word recall tests

Phonological Cued Recall

The first consonant(s) and vowel cluster of each target word was presented (e.g. "pi" for "pipa" over headphones to participants, who were then asked to verbally recall the whole word form. Partial responses and guesses were encouraged. Participants had up to 15 seconds for each response, but they could press the "next" button to move on to the next trial before the time limit. The responses were transcribed, and the word fragments (i.e. "pa" for "pipa") were scored for whole word accuracy.

Picture Naming

Animal pictures were presented on screen one at a time, and participants were asked to recall the name of the animal. They were also given the instructions to make guesses or to recall as many sounds as possible if they were not sure of their answers. Participants had up to 15 seconds for each response, but they could press the "next" button to move on to the next trial before the time limit. The responses were transcribed and scored for both whole-word accuracy and partial accuracy calculated using Levenshtein distance.

Analysis overview

Data from the training tasks, the phonological cued recall and picture naming tests were analysed separately, following the analysis plan from the pre-registration (https://osf.io/qkuy5). Following the pre-registered analysis plan, data from one participant was removed from analysis as their performance at the training task was below chance level, leaving the final sample with 77 participants. Words in the highly linkable semantic condition for which participants showed prior knowledge in the initial training were excluded from analyses (0.49% or 12/2448 data points for each task).

For phonological cued recall, whole word accuracy of the word fragment was used, as the task provided the starting sounds of the word as partial phonological information. Given this support and the relatively short response required, whole word accuracy was used in analysis, with no participants scoring 0[4]. Picture naming offered no phonological cues and required the retrieval of the complete phonological form, which increases task difficulty. As three participants scored 0 on whole word accuracy of the full phonological form, a graded measure was employed to capture partial phonological knowledge. Partial accuracy was calculated based on Levenshtein Distance by comparing the difference between a transcribed response and the target, accounting for changes such as insertion, deletion and substitution. Following Kurdziel and Spencer (2016), the Levenstein Distance score was converted to a matching proportion using the formula: matching proportion = 1 – (Levenstein Distance)/MaxLength, where MaxLength refers to the number of phonemes in the longest string out of the response and the target. Thus, a completely correct response will have a matching proportion of 1, whereas a matching proportion of 0 indicates the response does not contain any of the target phonemes.

A generalised linear mixed effects model was fitted for the phonological cued recall task and a linear mixed effects model was fitted for the picture naming task. For each word recall test, a mixed effects model was used to explore the effects of test session (immediate vs 1-week delay), semantics (less linkable vs highly linkable) and literacy skills composite. All dichotomous variables were contrasted using treatment contrasts with the immediate test session and less linkable semantics as baseline, respectively. The literacy skill composite (literacy) comprised the centred and standardised scores of the nonword reading subtest of TOWRE-2 and the spelling subtest of WRAT. Participants and stimuli were included as random effects, and we started with a theoretically and empirically meaningful random effect structure, simplifying it if convergence warnings appeared, following Matuschek et al. (2017). All frequentist mixed effects models were fitted using lme4 (Bates et al., 2025) in RStudio (version 2024.12.1, RStudio Team, 2020). Graphs were created using *ggplot2* (Wickham et al., 2024), and *emmeans* (van Rijn et al., 2017) was used to supplement the

[4] Partial accuracy was also calculated and analysed for phonological cued recall task following the same procedure as picture naming. The analyses using matching proportion confirmed that using partial accuracy for cued recall did not alter the pattern of results.

interpretation of interactions. Influential data was detected using influence.ME (Nieuwenhuis et al., 2012). Influential cases with a standardised dfBeta of beyond ±3.29 were removed before the same model was fitted again. Results of models with influential data would be reported separately if they yielded different results from the full model.

4.4 Experiment 5 Results

Training Performance

Before testing the key hypotheses, training task performance was analysed to better understand overall rates of learning. Accuracy for each block of the word-picture and picture-word matching tasks is shown in Table 15. Performance in the word-picture matching task improved from Blocks 1 to 2 ($\beta = .43$, $SE = .14$, $z = 3.16$, $p = .002$). Adults with higher literacy skills showed better overall performance ($\beta = .53$, $SE = .14$, $z = 3.77$, $p < .001$). No semantic effect was observed (i.e., Highly Linkable animals did not lead to significantly higher accuracy, $p = .19$). The results of the match-mismatch task were similar: literacy predicted overall accuracy ($\beta = .51$, $SE = .12$, $z = 4.30$, $p < .001$), but no semantic effect was observed ($p = .24$).

Table 15 Performance on Training Tasks in Experiment 5

Task	Less Linkable [M (SD)]	Highly Linkable [M (SD)]
Word-picture matching Block1	.67 (.47)	.72 (.45)
Word-picture matching Block2	.74 (.44)	.76 (.43)
Picture-word matching	.83 (.38)	.86 (.35)

Phonological cued recall

Accuracy was poorer at the 1-week delay (T2: mean = .30, $SD = .46$) than at the immediate test (T1: mean = .40, $SD = .49$), suggesting significant forgetting of word forms ($\beta = -.51$, $SE = .14$, $z = -3.55$, $p < .001$, see Figure 11a), contrary to hypothesis that performance would improve after one week (H1). Contrary to H4, word form recall was comparable for both semantic conditions, meaning there was no advantage for learning Highly Linkable animal names ($p = .14$, see Table 16).

On average, participants with better literacy skills showed better recall ($\beta = .69$, $SE = .14$, $z = 4.85$, $p < .001$). However, there was no evidence that better literacy skills supported better retention of phonological forms over the course of a week (*p* = .148), suggesting that participants with better literacy skills have higher initial recall, consistent with H2 (see also Figure 11b). But contrary to H3, they maintained this advantage across one week without showing stronger consolidation and neither did adults with poorer literacy skills show stronger forgetting. Contrary to H5, prior knowledge benefits were comparable across different levels of literacy skills (*p* = .240).

Table 16 Predictors of Phonological Cued Recall Accuracy in Experiment 5

Fixed Effects	Estimate	SE	z	p	
Intercept	-.83	.31	-2.70	.007	**
SessionT2	-.51	.14	-3.57	<.001	***
Highly Linkable Semantics	.62	.42	1.48	.139	
Literacy	.69	.14	4.84	<.001	***
SessionT2: Highly Linkable Semantics	-.09	.19	-.45	.651	
SessionT2: Literacy	-.23	.16	-1.44	.149	
Highly Linkable Semantics: Literacy	-.18	.15	-1.17	.240	
SessionT2:Highly Linkable Semantics: Literacy	.05	.22	.23	.816	

Random effects	Variance	SD
Participant (intercept)	.51	.72
Target (intercept)	.62	.79

Note: Literacy - Literacy skills composite of the standard scores of TOWRE-2 nonword reading and WRAT spelling subtests

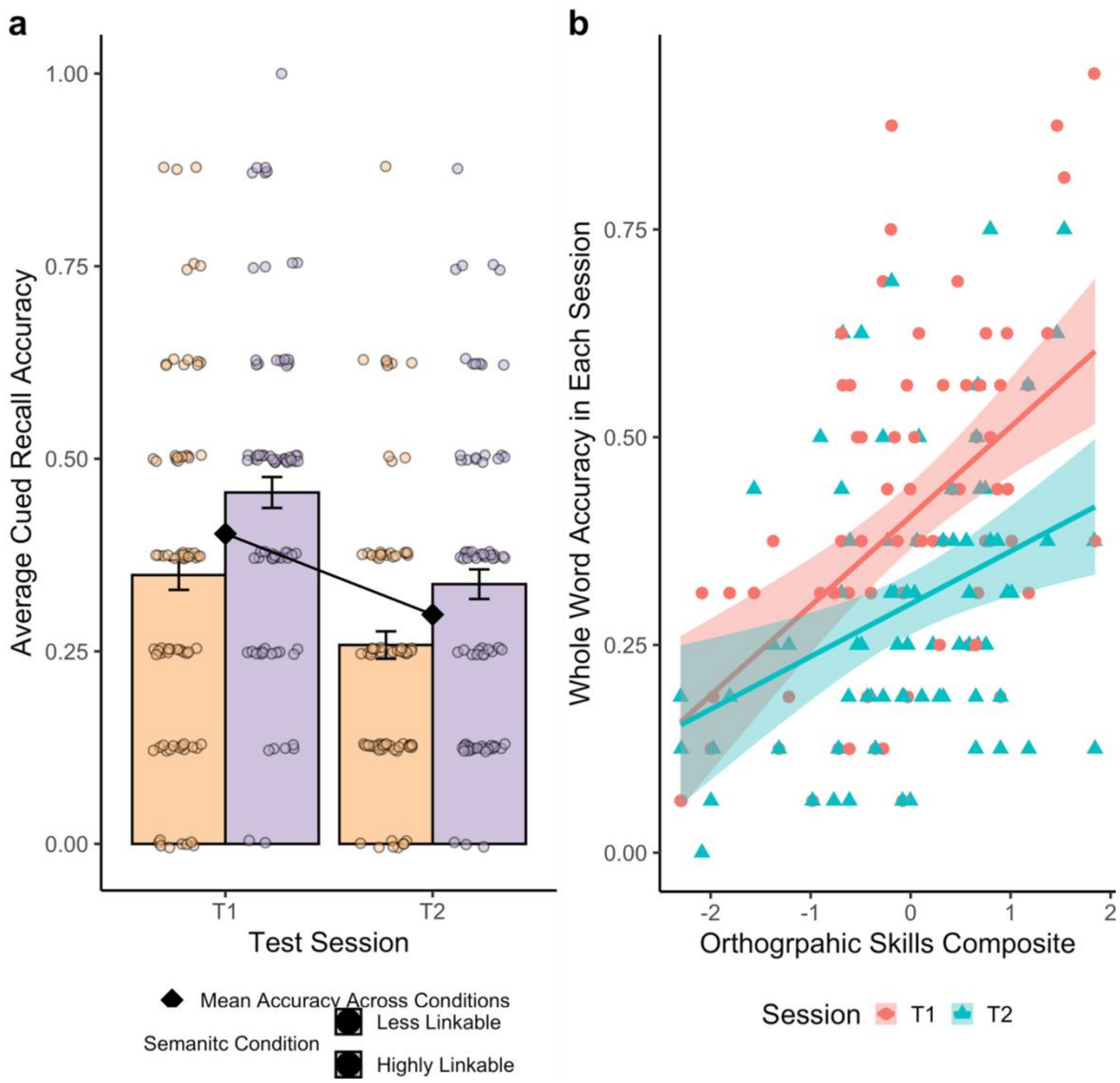


Figure 11a) Cued recall whole word accuracy for each test session by semantic condition, error bars represent standard error; and b) scatterplot showing whole word accuracy at each test session against literacy skills composite scores.
All points represent individual performance.

Picture naming

The matching proportion (MP), a Levenshtein Distance-based matching accuracy between the target and response, was higher at the immediate test (mean = .41, *SD* = .41, see Figure 12a) than at the 1-week delay test (mean = .27, *SD* = .37). Mixed effects model suggests significant forgetting (β = -.12, *SE* = .02, *df* = 2292.0, *t* = -6.14, *p* < .001), similar to phonological cued recall but in contrast to H1. In contrast to phonological recall, a semantic benefit was found for picture naming (β = .11, *SE* = .04, *df* = 18.05, *t* =2.48, *p* = .023): MP was higher for highly linkable semantic conditions at the immediate test, consistent with the semantic benefit hypothesised in H4. The difference between highly and less linkable semantic conditions became smaller after one week, as indicated by a significant, albeit weak, semantics by session interaction (β = -.05, *SE* = .03, *df* = 2292.0, *t* =-2.03, *p* = .043); yet, contrary to H3, this is potentially due to greater forgetting for highly linkable semantic conditions (see Figure 12a). However, this effect became insignificant (p = .063, see Table 17) when one influential case was removed; Bayesian mixed models (Appendix H) also found moderate evidence for no interaction (BF01 = 3.7).

Literacy skills predicted performance (Figure 12b): participants with higher literacy composite scores had higher MP overall (β = .14, *SE* = .02, *df* = 109.8, *t* = 5.84, *p* < .001). At the same time, more forgetting was also found among participants with better literacy skills (β = -.06, *SE* = .02, *df* = 2292.0, *t* = -2.95, *p* = .003), potentially due to better performance in the initial tests resulting in more room for forgetting.

Table 17 Predictors of Picture Naming Matching Proportions in Experiment 5

Fixed Effects	Estimate	SE	df	z	p	
Intercept	.36	.04	30.58	10.23	<.001	***
SessionT2	-.12	.02	2292.00	-6.14	<.001	***
Highly Linkable Semantics	.11	.04	18.05	2.48	.023	*
Literacy	.14	.02	109.80	5.84	<.001	***
SessionT2: Highly Linkable Semantics	-.05	.03	2292.00	-2.03	.043	*
SessionT2: Literacy	-.06	.02	2292.00	-2.95	.003	**
Highly Linkable Semantics: Literacy	-.01	.02	234.90	-.26	.793	
SessionT2:Highly Linkable Semantics: Literacy	.02	.03	2292.00	.77	.444	

Random effects	Variance	SD
Participant (intercept)	1.08	1.04
Target (intercept)	.38	.61

Note: Literacy - Literacy skills composite of the standard scores of TOWRE-2 nonword reading and WRAT spelling subtests

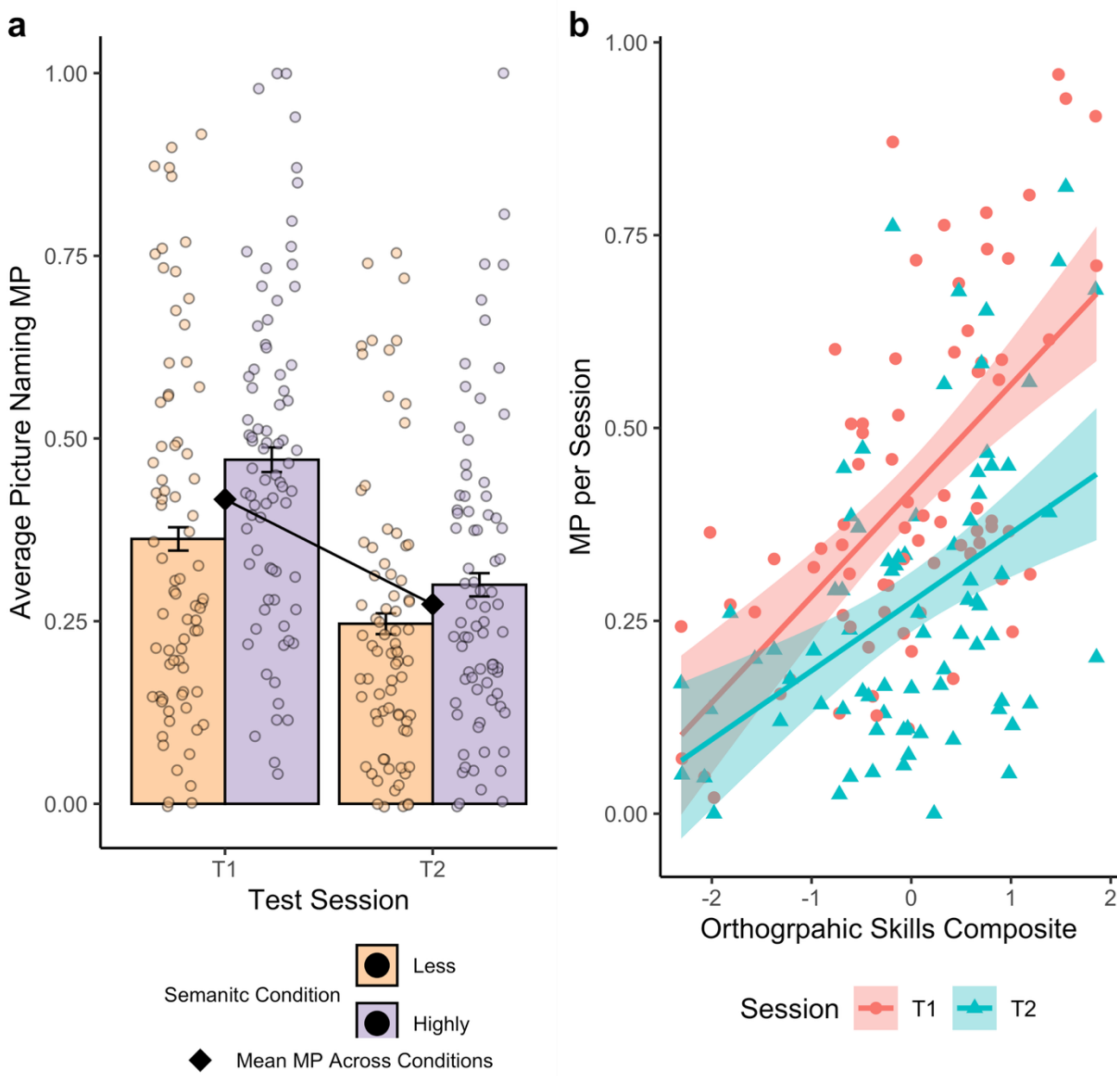


Figure 12 a) Picture naming matching proportion (MP) for each test session by semantic condition, error bars represent standard error; and b) scatterplot showing matching proportion at each test session against orthographic composite scores.
All points represent individual performance.

Exploratory analyses

In Experiment 1 (Chapter 2), an exploratory analysis showed that children's nonword repetition scores predicted the changes in the word form recall task across the 1-day offline consolidation period. In contrast, receptive vocabulary only predicted overall levels of word form recall. Therefore, while the above analyses used literacy skills as a continuous predictor of word learning performance, further exploratory analyses were conducted to examine whether phonological cued recall and picture naming outcomes would be similarly predicted by the same effects using standardised scores of expressive vocabulary and nonword repetition tasks to predict phonological cued recall and picture naming outcomes. Separate mixed-effects models were fitted with these two measures, replacing the literacy skills composite to explore if vocabulary and nonword repetition skills have specific contributions to the effects of semantics and session, respectively.

Vocabulary skills did not predict phonological cued recall accuracy ($p = .246$, Appendix I), potentially because this recall task focuses on the integrity of the phonological representation, rather than the depth of semantic knowledge. This is further exemplified as nonword repetition predicted phonological cued recall accuracy ($\beta = .27$, $SE = .13$, $z = 1.99$, $p = .046$). Neither vocabulary nor nonword repetition had a significant interaction with semantics (as for the main analyses) or sessions (*p*s > .14).

For picture naming, vocabulary was a marginal predictor of overall performance ($\beta = .05$, $SE = .02$, $df = 131.6$, $t = 1.97$, $p = .051$), which became a significant predictor after removing 4 influential data points ($\beta = .07$, $SE = .03$, $df = 125.8$, $t = 2.37$, $p = .019$). However, there were no significant interactions between vocabulary and semantics or session (*p*s > .2, Appendix I). Similarly, nonword repetition predicted picture naming MP ($\beta = .06$, $SE = .02$, $df = 125.9$, $t = 2.43$, $p = .017$), but there were no significant interactions with other factors.

4.5 Discussion

This study examined how literacy skills and prior knowledge support the learning and consolidation of novel spoken words in adults with varying language and literacy skills. Adults learned new spoken word forms that were associated with pictures of animals and were tested on their ability to recall them in response to an initial phonological cue or a picture immediately after training and one week later. Participants showed significant forgetting after one week. We observed benefits of local semantic knowledge (i.e., when new animals could be more easily linked with existing knowledge), but these benefits were task-specific and only observed for picture naming, which is more dependent on forming semantic associations between word form and referent. Literacy skills predicted individual differences in word recall at immediate and delayed tests; however, we did not find that better literacy skills led to greater offline improvements over time. Nor did we find that literacy skills were associated with the level of semantic benefit. We will discuss the findings by first examining the overall patterns of word learning and recall across one week, then the implications of individual differences in language and literacy skills on overall word learning and semantic benefits.

4.5.1 Changes in memory across one week

Performance in both phonological cued recall and picture naming decreased across the course of one week, suggesting that some of the newly learned words are forgotten across this interval, potentially due to decay and/or interference. This aligns with the broader memory and consolidation literature, which shows mixed findings in gains and declines in novel word recall following consolidation over delays in adults (Lindsay & Gaskell, 2013; H.-C. Wang et al., 2017). Following the CLS framework, developing a new lexical representation is a gradual process, including a consolidation period during which new words are embedded into the mental lexicon (Dumay & Gaskell, 2007). Previous evidence suggests that sleep benefits the recall of word form and word-picture associations (Kurdziel & Spencer, 2016). with suggestions that there are further benefits across several nights of sleep (Clay et al., 2007). The current results show a partial retention of the learned words across one week, with some forgetting. Potentially, only some of the learned words were successfully integrated into the neocortical system, whereas the remaining representations were lost due to interference and decay in hippocampal traces over the course of a week (Wixted, 2004).

One potential reason why we did not see the expected improvements and/or maintenance of performance as in previous studies relates to reconsolidation mechanisms. Reconsolidation is the process by which retrieval opportunities activate consolidated memories, returning them to a malleable state (Nader, 2015; Sinclair & Barense, 2019). While interference may be introduced and disrupt existing memories, reconsolidation can also lead to better consolidation and allow memories to be updated and refined (Lee, 2009; Rasch & Born, 2013). This is relevant here because gains in word recognition or recall performance after an extended period of delay tend to be found in published studies that included a 24-hour delay or repeated tests (James et al., 2019; McGregor et al., 2013; Tamminen et al., 2010); whereas maintenance or forgetting is more common after one week when an interim test was not included (Baxter et al., 2021; Storkel & Adlof, 2009; Tamminen

& Gaskell, 2013; but see Tamminen et al., 2013; for forgetting despite the inclusion of a post-sleep test). Therefore, the 24-hour test included in previous studies, which was absent in the current study, may serve as a reconsolidation opportunity that strengthens memory, rather than merely measuring recall after a one-day delay. Recently, Olsson (2022) examined novel word recall after a one-week delay with and without a next-day retrieval opportunity and showed a decline in performance when participants did not receive a within-day spaced retrieval or a post-sleep retrieval opportunity. This pattern suggests that memories benefit from reconsolidation at a retrieval opportunity following a consolidation period, leading to better retention over extended periods. The absence of the post-consolidation retrieval opportunity in the current study may contribute to the forgetting patterns.

We expected that literacy skills would predict the retention of newly learned words over a week, following evidence of atypical consolidation mechanisms in children and adolescents with dyslexia (Reda et al., 2021; Smith et al., 2018). However, adults with better literacy skills showed higher phonological form recall overall, and this advantage was consistent across both test sessions. That is, participants showed comparable levels of forgetting regardless of literacy skills, potentially because consolidation mechanisms can capitalise on the better encoding among adults with better language skills. Although adults with better literacy skills demonstrated superior overall performance, they unexpectedly showed greater forgetting in the picture naming task over the one-week delay. However, this pattern of forgetting should be interpreted with caution, as supplementary Bayesian analysis indicated no credible evidence for this interaction effect (Appendix H). One potential explanation could be that adults with higher literacy skills also showed better initial performance, leaving more room for forgetting than those with poorer literacy skills, who recalled fewer words initially. However, this finding was inconsistent with Landi et al. (2018), in which vocabulary and a reading composite were independent predictors of neural activity differences between words with and without consolidation opportunity at regions involved in retrieval and consolidation, which suggests an enhanced consolidation process in individuals with stronger language and reading skills.

4.5.2 "Global" linguistic skills predicting adults' word learning and recall

Literacy skills, which encompassed decoding and spelling proficiencies, predicted both cued recall and picture naming performance at the immediate and the one-week delay tests. This is consistent with the wider literature in dyslexia, which indicates that poor phonological and orthographic skills are associated with poor spoken word learning (Dumay et al., 2004; Henderson et al., 2013; Takashima et al., 2014). The current study also extends previous findings in children, whose vocabulary and nonword repetition are strong predictors of spoken word learning (Adlof & Patten, 2017). Consistent with Adlof & Patten (2017), our exploratory analysis showed that these two “global” linguistic skills contribute uniquely to different aspects of word learning. Vocabulary is a stronger predictor of adults’ picture naming due to the semantic demands of this task. Whereas nonword repetition predicted the performance of both phonological cued recall and picture naming, demonstrating the involvement of the phonological aspect across both tasks in adults. The involvement of nonword repetition is consistent with theoretical models of lexical quality (2007), highlighting that, even in adulthood, variations in existing phonological skills impacted the encoding and storage of new word representations. Furthermore, the current results also add to this literature by identifying decoding and spelling as key predictors for adults’ word learning. This may reflect an increased role of reading and writing, such that good decoding skills can support adults’ independent acquisition of new words through reading (Share, 1995). Whilst vocabulary, nonword repetition and literacy skills each predicted word learning in separate analyses, collinearity between these measures precluded the dissociation of their unique contribution within a single model. Future investigation using longitudinal or intervention approaches could help clarify whether literacy skills provide additional support beyond oral language abilities.

Literacy skills predicted adults’ overall performance in both phonological cued recall and picture naming tasks, providing insights into the mechanism of literacy impacting different aspects of word learning. The magnitude of literacy effects differed between the two tasks, with a larger effect in phonological cued recall than in picture naming, potentially because the latter can rely on lexical-semantic retrieval. Specifically, adults with poorer literacy skills appear to establish weaker phonological representations; therefore, the phonological cues might be less helpful in retrieving the full form in the phonological cued recall task. This pattern suggests that phonological processing is the primary mechanism affected by literacy abilities, consistent with Litt & Nation’s (C. D. Smith & Scarf, 2017) conclusion that phonological learning, rather than associative learning, is the primary impairment in dyslexia. However, as these two tasks differ in task demands and difficulties, future studies systematically varying these factors would provide a more precise comparison of the contribution of literacy skills to phonological and associative learning.

A dimensional approach to literacy was adopted in the current study, creating a composite measure of literacy abilities from decoding and spelling skills. Although we had pre-registered plans to recruit separate groups of adults with and without dyslexia, our final sample exemplifies the limitations of categorical approaches. Participants recruited for the "dyslexic" group showed relatively preserved decoding and spelling skills, suggesting well-compensated or relatively mild difficulties. In contrast, the "non-dyslexic" group showed a wide variability, reflecting the variability of literacy skills in the general population (Catts et al., 2024). This overlap led us to pool the participants and use literacy as a continuous variable, which arguably better reflects the natural variation of cognitive skills, including both clinical and sub-clinical individuals (Astle et al., 2022; Snowling & Hulme, 2012). As illustrated in Appendix Figure G-1, the two groups displayed overlapping profiles in standardised tasks such as word reading, expressive vocabulary and nonword repetition (see also Appendix Table G.1), with group differences only demonstrated in nonword reading and spelling, which formed the basis of the continuous literacy measure in the main analyses. Nonetheless, this approach may limit our ability to generalise the results to populations with more severe impairments.

4.5.3 Prior knowledge-supported "local" semantics in spoken word learning

In the current study, "local" semantic information that is easier to form links with existing knowledge benefited performance during picture naming, but this benefit was not seen at the point of initial training or in phonological cued recall. Furthermore, there were no interactions between this prior knowledge semantic benefit and literacy skills in any task, suggesting that the semantic effect in picture naming was consistent across the literacy continuum. Therefore, the current results indicate that the ease of associating with prior knowledge supports forming links between word form and meaning but not aiding word form encoding or retrieval.

The lack of a semantic effect in the phonological cued recall task is somewhat surprising, as previous research suggests that semantic support, particularly when building on prior knowledge, can facilitate phonological form recognition, despite semantic information not being directly required in this task (Havas et al., 2018). Our previous findings in adults

(Experiment 2/Chapter 2 of this thesis) similarly showed the benefits of prior knowledge-supported semantics extending to enhancing recall performance of phonological representations. Furthermore, across a number of reading and nonword serial recall tasks, Savill et al. (2019) found that participants who performed more poorly in a nonword task showed greater reliance on/activation of lexical-semantic effects for encoding and retention of phonological forms in the verbal short-term memory during the immediate serial recall task. Prior research into familiar word processing further suggests that individuals with poorer phonological skills, including those with dyslexia, may use their relatively spared semantic knowledge to compensate for the more effortful phonological processing (Lukic et al., 2024; Van Rijthoven et al., 2022). Our current results suggest that this semantic compensatory effect could be restricted to the processing and retrieval of familiar items, but not generalised to support the establishment of new lexical representations, echoing one previous study with French dyslexic university students (Rasamimanana et al., 2020) by drawing from a broader demographic. The lack of a semantic compensatory effect in the current study highlights the importance of understanding the boundary conditions of this previously reported facilitatory effect.

However, Hawkins & Rastle (2016) argue that learning goals may determine if semantic information benefits lexical representations. When participants were instructed to learn the spoken word form, form recognition and recall were comparable between words paired with pictures and words presented in isolation. Likewise, in the present study, we did not provide explicit instructions for participants to use their semantic knowledge of animals to support learning. This suggests that without explicit instructions or prompting to leverage semantic knowledge, semantic links may not be a strategy spontaneously used by participants, leading the highly linkable semantic advantage to emerge only when the picture naming task directly requires semantic retrieval.

Different theories of prior knowledge support in learning diverge in their predictions about what type of information is most beneficial to word learning. Schema-based theories, such as the CLS framework according to McClelland (2013) and the Schema-Linked Interactions between Medial prefrontal and Medial temporal regions framework (SLIMM, van Kesteren et al., 2012), suggest a facilitatory effect when new information is consistent with existing knowledge. The semantic manipulation of the current study is dependent on visual and conceptual similarity of the stimuli to existing animals to activate prior knowledge, whereas less linkable stimuli could be less closely associated with existing knowledge, which may result in a novelty effect that can also facilitate memory (for a review, see Lorents et al., 2023). As both Highly and Less Linkable stimuli contain elements of novelty and familiarity, it is likely that both schema-congruency and novelty processes are involved in different degrees, potentially explaining why a prior knowledge semantic benefit only emerges in the picture naming task, which has higher semantic retrieval demands, but not in the phonological cued recall task.

4.6 Conclusion

In conclusion, the present study examined the contribution of consolidation processes and semantic knowledge to spoken word learning in adults with a range of literacy skills. Adults with poorer literacy skills showed weaker spoken word learning, even when there was no reading requirement and when new words were taught explicitly (i.e., through direct instruction, as opposed to more implicit forms of learning). This finding is consistent with models of reading, such as the Lexical Quality Hypothesis (Perfetti, 2007), indicating poorer acquisition of new lexical representation by those with weaker phonological skills. The retention of recently learned words across the literacy skill continuum revealed complex patterns: comparable forgetting was found in the phonological cued recall task. However, for the picture naming task, we observed greater forgetting among adults with stronger literacy skills, though they still maintained superior performance at the one-week delay due to better initial learning.

Regarding semantic support, participants did not automatically use semantic information to aid word form learning; instead, semantic benefits only appeared when the task involved recalling word forms as associated with their semantic referents. The semantic benefit of the picture naming task emerged in the immediate test and persisted after consolidation, further demonstrating that semantic support operates separately from the offline consolidation process and may offer a direct route to cortical integration, consistent with McClelland (2013). The consistency of the semantic effect across the literacy continuum suggests that semantic compensatory mechanisms in individuals with weak literacy skills that have been observed in previous research may be specific to familiar word processing (i.e., once words are better established in the lexicon) rather than extending to novel word learning. However, whether stronger prior knowledge semantic benefits may emerge with greater differences between the two conditions, or under different learning conditions, such as incidental learning or with orthographic support, remains an open question for future studies.

Chapter 5 General Discussion

The work presented in this thesis aimed to investigate adults' and children's word learning over the course of one week and the contribution of prior linguistic knowledge within this timeframe. Using measures of word recall across different test schedules, we examined how memory for new words changes over varying off-line consolidation periods in each age group. In a series of substantial studies that use parallel innovative learning materials the contribution of prior linguistic knowledge was examined in two key ways: (i) by manipulating the "local" semantic information from pictures, which varied in the ease of forming connections with existing knowledge, and (ii) by measuring "global" individual differences in phonological working memory, literacy skills, and vocabulary, a proxy for semantic knowledge.

The results across four experiments with children aged 9 to 11 and adults revealed a stronger offline consolidation benefit in children than in adults, both across one-day and one-week delays. This developmental difference in consolidation manifested as a greater improvement across tests that spanned at least one overnight sleep opportunity, but was not observed over periods of daytime rest or repeated tests within a day. Thus, children's larger improvements across one week could arguably be underpinned by overnight consolidation processes. The role of "local" prior semantic knowledge was more inconsistent, mainly benefiting adults' word learning under specific learning conditions and particular recall tasks that tap into semantic representations. In contrast, "global" prior knowledge (i.e., vocabulary skills) consistently predicted children's word learning performance. The effects of global vocabulary were not observed among a relatively homogenous university-based adult sample; however, individual differences in vocabulary and phonological skills predicted word learning in a group of adults with greater variation in decoding and spelling skills. These findings emphasise the importance of incorporating developmental and individual perspectives into existing models and theories of vocabulary learning, which are largely based on adults' learning behaviour.

5.1 Summary of experimental findings

Chapter 2: Experiments 1 and 2 examined whether providing meaningful pictures alongside new word forms enhances word learning, and more specifically, whether there are additional benefits when this semantic information can be more easily linked to prior knowledge. Another aim of the study was to determine if any observed semantic benefit supports word recall immediately after learning, or if it requires a period of offline consolidation to emerge. Theoretical accounts, such as the Complementary Learning Systems (CLS, McClelland et al., 1995) and the information overlap to abstraction (iOtA, Lewis & Durrant, 2011) model, offer diverging predictions as to *when* semantic support for new learning should emerge. Children and adults were taught novel word forms paired with three picture types: pictures with no semantic information, semantically related pictures that were difficult to associate with existing knowledge (Less Linkable condition), and semantically related pictures that closely aligned with familiar concepts, i.e. familiar animals (Highly Linkable condition). Adults received fewer exposure (5 times) and repetition (1 time) opportunities during the training phase than children (8 exposures and 3 repetitions), such that the two age groups were matched in recall and picture naming performance at the immediate test. Memory was assessed immediately after learning, and the same items were tested again using the same tasks one day and one week later.

Results showed that the recall of word forms and word-picture association improved after offline consolidation opportunities, with children showing larger gains than adults both after a one-day and a one-week delay, despite equivalent performance at the immediate test. Contrary to predictions, semantic information did not enhance children's word form recall, and no benefit of prior knowledge was found in picture-word association recall. However, adults demonstrated semantic effects in both recall tasks, with additional benefits from prior knowledge-supported semantic information. These semantic effects were observed immediately after learning, suggesting that prior knowledge is activated to facilitate efficient word learning. Analyses of individual differences in children suggested that vocabulary and nonword repetition, which indexes phonological short-term memory capacity (Gathercole & Baddeley, 1989), predicted overall word learning performance, with stronger overnight consolidation found in children with better nonword repetition skills. These results suggest that semantic support and memory consolidation are two independent mechanisms that support word learning to varying extents at different developmental stages: semantic support may be relatively more weighted for adults, who have a more mature language system and greater prior knowledge, whereas children may depend more on offline consolidation mechanisms. However, further experiments were needed to understand the mechanisms underpinning children's superior offline gains to better understand this developmental difference.

Chapter 3: Experiments 3 and 4 aimed to better understand why children showed bigger offline gains in new word recall over one day and one week than adults did in Chapter 2. One potential explanation for the bigger consolidation benefits in children is the increased slow wave sleep at this point in development, though periods of daytime rest can also support memory stabilisation and protect recently learned words from decay (Mednick et al., 2011; Wamsley, 2022). We investigated the contribution of this protection by including a 10-minute wakeful rest after the immediate test, compared to remaining active during this time, to examine if post-learning rest is more beneficial to maintaining and consolidating novel words in children (Experiment 3) and adults (Experiment 4). In addition to the immediate test, recall of the novel word forms was tested following the 10-minute delay and again after a one-week delay to establish the immediate effects and long-term benefits of wakeful rest. Novel words were paired with pictures from the Less and Highly Linkable conditions in Chapter 2. The non-semantic picture condition was dropped from this study as the benefit of the presence of semantic information compared to abstract picture referents was established previously in adults of Experiment 2, and to reduce learning demands and length of the training phrase for Experiments 3 and 4. Adults and children received the same amount of training and were tested on their phonological and word-picture recall memory immediately after learning, after a 10-minute delay, and one week later. During the 10-minute delay, children and adults either engaged in an eyes-closed wakeful rest (wakeful rest) or they completed timed spot-the-difference puzzles (active wake), which kept participants engaged in the nonverbal task throughout the 10-minute delay.

Regardless of age group, the wakeful rest and active wake groups showed comparable performance after the 10-minute and one-week delays, suggesting no wakeful rest benefits in recalling newly learned words either immediately after wakeful rest or in supporting longer-term memory. At the one-week delay test, children showed improved recall of the new word forms following offline consolidation opportunities, whereas adults' word form recall performance remained stable, and they showed some forgetting in the picture naming task. Developmental differences were observed at the one-week delay test, supporting the proposal that greater offline consolidation benefits in childhood depend on sleep-based offline consolidation mechanisms, and do not occur during periods of cognitive downtime or over repeat tests within a day. 'Global' vocabulary knowledge was a highly significant predictor of individual differences in children's performance, but not among adults, potentially because adults have sufficient knowledge based to support their learning of novel words.

Chapter 4: The final experiment took an individual differences approach to better understand the role of prior knowledge in supporting new word recall in adults. Previous studies have reported a smaller role of sleep in consolidating novel words among adults and children with dyslexia (Ben-Zion et al., 2023; F. R. H. Smith et al., 2018), while other studies suggest a compensatory role for semantics in individuals with dyslexia (Moojen et al., 2020; van der Kleij et al., 2019). Therefore, this experiment examines whether the size of consolidation across one week varies among adults with a wider range of literacy skills, including those with dyslexic literacy profiles. The learning and recall of novel words paired with pictures from the Less and Highly Linkable semantic conditions were examined for individual differences in the support from prior knowledge-consistent semantic information. We also explored that individuals with weaker literacy skills could show a greater dependency on prior knowledge than on consolidation mechanisms during word learning.

It is expected that adults with poorer literacy skills would show weaker consolidation of novel words, but that this could be compensated for by a greater reliance on semantics, which can be used to support the learning of words with stronger links to existing semantic knowledge. Adults' word recall and picture naming were assessed immediately after learning and after a one-week delay. Critically, we omitted the one-day delay test to investigate whether a delayed retrieval test contributes to the one-week consolidation benefits observed in the experiments of previous chapters.

Adults showed significant forgetting of both word forms and picture-form associations over one week. Contrary to predictions, adults with poorer literacy skills showed comparable memory preservation to those with stronger literacy skills, over the one-week delay, despite weaker initial learning. While both groups showed some forgetting, their rate of decay was similar, suggesting intact consolidation processes across the spectrum. In addition, words paired with pictures that drew more on prior knowledge benefited picture naming performance, but not word form recall, across the sample, with no evidence that adults with dyslexic traits benefited more from semantic support. This also suggests that prior semantic knowledge is only recruited when the recall task demands semantic involvement, but it is not used spontaneously to support recently learned lexical representations. Aligning with this, exploratory analysis showed that vocabulary abilities in adults did not predict word form recall performance but did predict picture naming performance. Instead, word-form memory was predicted by nonword repetition (i.e., phonological STM).

The following discussion first examines the mechanisms underlying developmental differences in offline consolidation of new vocabulary, including the role of reconsolidation opportunities. Next, I consider the role of "local" semantic connections in supporting word form learning, focusing on when this benefit appears, and to whom these connections benefit learning across development. I will then turn to individual differences in linguistic skills, examining how variations in varied vocabulary and phonological abilities impact the "global" patterns of learning and consolidation in children and adults. Finally, we will consider some limitations and the theoretical and educational implications of these findings.

5.2 Developmental differences in the contribution of memory consolidation systems

Word learning draws on various inputs and processes, including integrating memory processes (Wojcik, 2013). In particular, sleep has been identified as a critical state for memory consolidation (Davis & Gaskell, 2009), building on the CLS framework (McClelland et al., 1995), which proposes a two-system approach for initial encoding and long-term integration. The active systems consolidation account suggests that memories stored in the hippocampal region are reactivated during slow wave sleep (SWS), such that memories are selectively transferred and integrated with long-term existing knowledge distributed across the neocortex (Born & Wilhelm, 2012). In the context of word learning, memories of novel words are therefore strengthened after sleep (James et al., 2017; Weighall et al., 2017). Although these theories were initially developed based on adult data, simulation, and animal models, studies over the last two decades have demonstrated that children also benefit from sleep-based consolidation processes (Ashworth et al., 2014; Wilhelm et al., 2008). Moreover, due to changes in sleep architecture across development, the duration of SWS and other key sleep consolidation parameters accounts for double the proportion of overnight sleep and naps in children than in adults (Ohayon et al., 2004; van Rijn et al., 2023). Building on these developmental changes in sleep architecture, Experiments 1 and 2 replicated children's superior consolidation after one-day and one-week delays (James et al., 2019, 2023; Peiffer et al., 2020; Wilhelm et al., 2012). Importantly, this was observed despite ensuring adults' levels of learning at immediate test were equivalent to children's, thus eliminating differing encoding strength as a potential source of consolidation difference (Drosopoulos et al., 2007)

Nevertheless, it is worth considering additional factors that may have contributed to these developmental patterns. For instance, Wilhelm et al. (2011) the anticipation of a subsequent test could strengthen memory (though see Ashton & Cairney, 2021). From the post-retention questionnaire of Experiments 3 and 4, most adults expected a test following the 10-minute retention period, whereas most children did not. Similar patterns likely held in Experiments 1 and 2, where children were told their memories of the words could be tested, compared to adults who specifically signed up for test sessions they could attend, which may impact their perceived importance or usefulness of the words (van Rijn et al., 2017). Children are also more likely to maintain a more regular sleep schedule during school days (Kitsaras et al., 2021) than adults, which might impact the amount of consolidation achieved. While developmental differences in SWS architecture remain a possible account for enhanced consolidation in children, these uncontrolled factors are important factors that could impact the extent of the developmental difference and warrant consideration in future research.

Although the active system consolidation account provided a sleep-based mechanistic explanation for developmental differences in the word consolidation trajectory, the current thesis also considered alternative processes that may take place during offline consolidation and examined whether they could contribute to the developmental differences in the timecourse of word learning. The passive protective view of sleep suggests that newly learned words can be protected from interference and forgetting, as new learning and encoding are minimised during sleep (Ellenbogen et al., 2006; Wixted, 2004). Furthermore, this interference-free state also allows other non-sleep-specific consolidation processes to take place. For instance, the opportunistic consolidation theory (Mednick et al., 2011) suggested that a period of reduced interference shortly after learning can stabilise and consolidate new word traces. Accordingly, other offline states of reduced interference could potentially contribute to children's greater consolidation benefits; one such offline state is wakeful rest. Wamsley (2022) proposed that a short offline waking rest supports the early stages of stabilising recently formed memory traces, which are then further consolidated during subsequent sleep.

Experiments 3 and 4 tested whether a short post-learning wakeful rest could account for children's stronger consolidation without sleep-based consolidation opportunities, in order to understand if processes that are common to both during quiet daytime rest and overnight are driving the developmental difference. A 10-minute post-learning wakeful rest provided a cognitive downtime opportunity for memory stabilisation, yet neither children nor adults showed enhanced word recall compared to an active control condition (See Table 18). Thus, it is unlikely to explain children's greater consolidation benefits in word recall at the one-week test. This leaves open the explanation that developmental differences in consolidation are driven by overnight consolidation, building upon sleep architecture differences reported by previous active systems consolidation literature (Wilhelm et al., 2008). Nevertheless, several limitations prevent a definitive conclusion from being drawn, including the brief duration of wakeful rest compared to overnight sleep and the unfamiliarity of the wakeful rest procedure compared to habitual napping or overnight sleep. Given these limitations, future research across a longer period of wakeful rest training is needed to fully evaluate the contribution of daytime wakeful rest to developmental differences in long-term consolidation.

It should also be noted that repeated presentation and testing opportunities are also embedded in the tests, which could offer further encoding opportunities (e.g. in prompting for meaning recall in Experiments 1 and 2, and in presenting the picture stimuli during picture naming tasks). Prior studies have demonstrated that repeated exposure and testing, especially testing sessions that are spaced across several days, have long-term memory benefits across age groups (Antony et al., 2017; Bencze et al., 2024; Roediger & Butler, 2011; Sobel et al., 2011). However, repeated testing alone is also an unlikely explanation for the developmental differences observed in Chapters 2 and 3. If children benefiting more than adults from additional recall and testing opportunities explains the developmental difference observed in Chapter 2 and in previous studies, then children's better recall in Chapter 1 should also have been found at the recall opportunity that followed a 10-minute retention period in Chapter 3. Yet, a developmental difference was only observed at the one-week delay test, following an extended offline consolidation opportunity

Table 18 Summary of offline consolidation and semantic effects across all experiments

		Word Form Recall				Picture Naming				Global support
Exp	AgeGrp	10-min delay	1-day delay	1-week delay	Local semantic benefit	10-min delay	1-day delay	1-week delay	Local semantic benefit	Vocabulary
1	Children		↑	↑	✗		↑	↑	✗	✓
2	Adults		↔	↑	✓		↔	↑	✓	
3	Children	↔		↑	✗	↔		↔	✗	✓
4	Adults	↔		↔	✗	↔		↓	✗	✗
5	Adults			↓	✗			↓	✓	✓ (Picture Naming Only)

Notes: Consolidation effects are in comparison with the previous test session (e.g. 10-minute delay test compared with immediate test for Chapter 3); ↑ indicates improvement, ↓ indicates performance decline and ↔ indicates maintenance.

Semantic benefits displayed the comparison of Less vs Highly Linkable only for Chapter 2

Greyed-out cells indicate that this test was not included.

5.3 Reconsolidation opportunities from post-sleep retrieval

Adults' one-week retention differs across experiments varying in the availability and timing of interim retrieval tests. Long-term consolidation was better when an interim test occurred after an offline consolidation opportunity (one-day delay) compared to shortly after learning (10 minutes) or no interim test. Specifically, in Experiment 2, adults showed long-term improvement at the one-week delay tests when a one-day test opportunity was included. In contrast, in Experiment 4, which included a same-day test opportunity 10 minutes after the immediate test, maintenance and decline were found in word form recall and picture naming, respectively; whilst forgetting in both tasks was demonstrated in Experiment 5 without the interim test (See Table 18). One potential explanation for this pattern draws on reconsolidation theory (C. D. Smith & Scarf, 2017), which explains why repeated tests spaced out over an extended timescale could yield better long-term consolidation. A delayed test – such as the one-day delay test in Experiment 2, reactivates consolidated memory traces and allows the trace to be updated, modified, or strengthened, resulting in a more stabilised and strengthened long-term representation. Critically, this account suggests that reconsolidation benefits only occur for traces that are previously consolidated; therefore, a repeated test that occurs shortly after encoding, such as the post-retention test in Experiment 4, may not engage this reconsolidation mechanism effectively. The interpretation of this cross-experiment comparison aligns with studies in the spaced retrieval literature, which have found that spaced retrieval interleaved with sleep opportunities resulted in better retention compared to spaced sessions within the same day (Olsson, 2022; Rodríguez-Gonzalo et al., 2024). However, given that these observations stem from comparisons across experiments that differ in several significant ways, including the number of items, levels of initial performance, and participant background characteristics, direct experimental manipulation of retrieval timing is necessary to establish whether the observed pattern reflects the reconsolidation process or other differences in experimental design.

An important question for future research is whether children's superior consolidation also extends to enhanced reconsolidation benefits. Children have a stronger offline consolidation mechanism than adults (Wilhelm et al., 2008), which results in stronger, more stable memory traces to be successfully retrieved at the one-day delay test to trigger reconsolidation. As a result, this could mean a more comprehensive strengthening and updating of the reactivated memory and stronger long-term consolidation. Across

Experiments 1 and 3, children appear to show bigger improvements at the one-week delay test following the one-day delay test in Experiment 1 than from the 10-minute delay test in Experiment 3, the latter only improved in word from recall but not in picture naming. Potentially, this difference is due to the post-consolidation retrieval and reconsolidation opportunity at the 1-day delay test. If the cumulative amount of sleep consolidation opportunities alone predicts the size of long-term consolidation, we should expect a smaller offline consolidation for Experiment 1 than Experiment 3, which has an additional day of offline consolidation between the interim test and the one-week delay test. Nevertheless, this interpretation should be considered with caution due to other differences in experimental design and warrants further studies which directly compare the two timescales. Examining developmental differences in the reconsolidation account would advance the understanding of sleep-based consolidation theories. Firstly, since the reconsolidation account requires reactivation and modification of memory traces (Nader, 2015), rather than simply protecting memory from deterioration, developmental differences in reconsolidation would provide evidence for active consolidation being the driver of children's stronger memory processes. Secondly, separating initial consolidation from subsequent reconsolidation benefits would further clarify the timescale of vocabulary learning, revealing how developmental differences might be involved in both stages. Furthermore, if reconsolidation plays an important role in the developing consolidation mechanism, this could potentially inform pedagogical practices (Kroneisen & Kuepper-Tetzel, 2021) and align teaching and revision schedules with consolidation timeframes.

5.4 "Local" semantic connections support for word-form learning

The picture stimuli used in this thesis were developed based on the prior knowledge or schema (McClelland, 2013; Tse et al., 2007). It is hypothesised that the Highly Linkable condition, which consists of unfamiliar breeds or species of real animals, could form connections with prior knowledge of the corresponding familiar animals, and participants can use this prior knowledge to support better word learning (e.g. *pipa* form connections with the prior knowledge of frogs more easily, and these connections can strengthen word form learning). The results across experiments suggest that this local semantic connection benefit is limited to mostly tasks that involve semantic retrieval, e.g. picture naming, in adults.

Before considering when in the timecourse semantics exerts benefits, we should first acknowledge that alternative theoretical frameworks have made different predictions about the nature of semantic benefits, building upon different conceptions of semantic relationships. Similar to the schema account, network-based accounts emphasise the connection between different semantic nodes, across which activation can spread across the network. Prior studies suggest that adults' semantic networks are structured to support efficient processing, with local clusters of interconnected concepts and fewer nodes between distant clusters (Steyvers & Tenenbaum, 2005). Therefore, novel words with new semantic information that fall in one of these dense clusters of well-connected nodes are more likely to benefit from richer connections (Mak & Twitchell, 2020). Under this view, the Highly Linkable animals used here could benefit from a richer established network of animal knowledge, concurring with the predictions made based on the CLS framework and the results of Experiment 2. In contrast, studies examining the effects of semantic neighbourhood density suggest that information that falls into a dense semantic network, i.e. with closely connected prior knowledge, is more prone to interference and harder to learn (Fieder et al., 2019; James et al., 2023; Storkel & Adlof, 2009; Tamminen et al., 2013). Thus, a semantic neighbourhood approach would predict that the Less Linkable stimuli might be more beneficial. The modest semantic effects found in the experiments presented here do not provide clear support for either account, likely reflecting the complex nature of semantic manipulations that span multiple dimensions, calling for more studies to systematically contrast different semantic relationships to develop a more cohesive and precise framework to account for how semantic information supports new learning.

The comparable performance between the two semantic conditions could suggest that both Highly and Less Linkable conditions may have recruited a combination of schema-based and episodic consolidation processes, varying in the amount of support from each process rather than the type of support. The schema-linked interactions between medial prefrontal and medial temporal regions (SLIMM) framework (van Kesteren et al., 2013, 2012) accounted for memory facilitation of schema-congruent information through activating existing knowledge and incongruent information through creating new episodic memory. However, van Kesteren et al. (2012) also proposed that less congruent information, which only partially activates schematic support, would lead to less effective encoding than both extremes of the congruency continuum. Both Less and Highly Linkable stimuli used here could fall into these intermediate spaces, neither strongly activating prior knowledge nor sufficiently novel to generate new episodes, accounting for the weak semantic benefit observed in some tasks. This also raises the question of whether the contributions of distinctiveness and prior knowledge support can be meaningfully distinguished in my experiments. For instance, the Less Linkable stimuli were created to activate a general schema of animals, but to be hard to form close connections with any specific animal. Inevitably, these stimuli appear more distinctive than unfamiliar breeds of real animals, where distinctiveness is another factor that promotes a stronger memory (Reggev et al., 2018). Further research employing neuroimaging methods could clarify the involvement of these memory mechanisms by examining medial prefrontal and medial temporal activations under similar ambiguous stimuli, which could clarify how stimuli at different points of the continuum would be processed.

5.5 The timecourse of "local" semantic support

One theoretical contribution of the experiments presented here is the timecourse of prior knowledge support during word learning and consolidation. Building on this foundation, the current thesis examined whether the ease with which connections can be made between new semantic information and existing knowledge influences word-form learning, by how readily new information can draw on prior knowledge to form semantic associations. This follows schema-based accounts such as the iOtA model (Lewis & Durrant, 2011) and an extension to the CLS framework, which explicitly considers the role of consistency in prior knowledge (McClelland, 2013; Tse et al., 2007). While both theories propose a benefit from greater schematic consistency, they diverge in the prediction of *when* in the word learning process this benefit can be expected. The iOtA model suggests that schema-consistency strengthens novel words by promoting integration with existing knowledge during sleep, while McClelland (2013) predicts that schema-consistent information reduces the need for gradual incorporation and can be acquired rapidly. Building on these theoretical predictions, the current thesis manipulated the degree to which semantics can be associated with existing knowledge. For unfamiliar breeds of known animals in the Highly Linkable condition, stronger semantic links would support better learning and the establishment of a stronger lexical representation. In contrast, fictitious animals in the Less Linkable condition may draw on schematic knowledge of animals more broadly but lack specific links with particular local knowledge.

When semantic connections with prior knowledge benefitted adults' word learning, Experiments 2 and 5 showed that these benefits were apparent at the immediate test and were maintained across subsequent tests without the benefits being modulated by consolidation. However, the semantic benefit appeared to be sensitive to task demands and experiment manipulations. For picture naming, which included a semantic cue to retrieve the word form, Highly Linkable items showed an advantage over Less Linkable items. This suggests that recently learned words with richer associations with prior knowledge consistently facilitate semantic retrieval. In contrast, word form recall, which required participants to produce the full phonological forms when given a phonological cue, showed semantic benefits only in Experiment 2 and not in Experiment 5. One key difference between these experiments was the presence of an abstract "non-semantic" pattern condition in Experiment 2, which could have highlighted the salience of semantic content across all conditions. The inclusion of a picture description task as part of the training in Experiment 2 may also have heightened attention towards semantic features and promoted deeper semantic processing (Craik & Tulving, 1975; Frishkoff et al., 2011). This task- and experiment-specific pattern suggests that semantic benefits provide limited transfer to strengthen word form representations.

Prior studies contrasting the presence or absence of semantic information during word learning found that semantics might initially divert attention and encoding resources from learning novel word forms, with recall and lexical integration benefits of semantics emerging only after a one-week delay (Dumay et al., 2004; Henderson et al., 2013; Takashima et al., 2014). Nevertheless, the findings reported in the current thesis are consistent with more recent studies manipulating the degrees of prior knowledge support, such that when semantic or lexical prior knowledge benefits were found, the difference could be observed from the immediate test (Angwin et al., 2014; James et al., 2019, 2023; Tamminen et al., 2013). Importantly, offline consolidation did not enhance the semantic benefits found in this thesis, such that the relative advantage of prior knowledge did not increase across delays. This finding is inconsistent with the iOtA model's predictions of a sleep-based schematic benefit (Lewis & Durrant, 2011). Instead, words in both conditions were consolidated similarly, suggesting that prior knowledge provides a lasting benefit that is separate from any effects of memory consolidation, with memory consolidation and prior knowledge acting as independent mechanisms to support word learning. Therefore, the experiments presented here are more consistent with the proposal of McClelland (Havas et al., 2018) than with the predictions derived from the iOtA model. However, contrary to the CLS prediction, we did not find enhanced consolidation for items with less support from prior knowledge, which should be more reliant on hippocampal encoding, and which should therefore result in greater offline consolidation change. The hippocampal pathway appears to support neocortical integration irrespective of prior knowledge support, benefitting from offline replay and reactivation (Havas et al., 2018). Both Less and Highly Linkable associations to prior knowledge showed equivalent consolidation gains, thus preserving the advantage of high prior knowledge support items (Angwin et al., 2014; James et al., 2023).

5.6 Integrating developmental perspectives into models of semantic prior knowledge

The experiments presented in this thesis also explored developmental differences in prior knowledge engagement during semantic learning. The semantic benefits discussed in the previous section were found primarily in adults, while children in Experiment 1 showed comparable recall performance across semantic conditions. In Chapter 1, we proposed that adults and children may rely on different mechanisms to support novel word learning based on their developmental strengths. Whilst children have a more enhanced memory consolidation mechanism (James et al., 2019, 2021; Peiffer et al., 2020; J.-Y. Wang et al., 2018; Wilhelm et al., 2012), vocabulary grows with age and shapes semantic networks (Cosgrove et al., 2023; Hills et al., 2009; Metsala & Walley, 1998). This developmental change likely also reflects the availability and strategic engagement of prior knowledge. As the reliance on prior knowledge in declarative tasks increases with age (Brod & Shing, 2019), it may be that adults are more adept at engaging prior knowledge to support learning. Furthermore, Bird (2012) demonstrated that semantic processing depends on a strong prior linguistic knowledge foundation, as the semantic advantage was bigger in native than non-native speakers. Extending this logic to a developmental comparison, children have a smaller linguistic knowledge foundation and might therefore show less reliance on semantic processes under the present experimental conditions.

In Experiments 1 and 2, a direct developmental comparison showed that children performed comparably for both semantic conditions, whereas adults demonstrated an advantage for the Highly Linkable condition relative to the Less Linkable condition. Critically, adults' Highly Linkable performance was similar to children's performance on both conditions, while their Less Linkable condition fell below this level. This pattern suggests that adults leveraged prior knowledge connections when they were available but showed poorer learning when these connections were sparse, whereas children's learning, which was less reliant on prior knowledge connections, was by stronger consolidation mechanisms (Section 5.2). This interpretation is consistent with a prior study with school-aged children, who showed comparable levels of learning when novel word-object pairs were presented with and without information about their function, implying that children's lexical learning does not benefit from the semantic information supplied, despite showing good memory of the semantic information (Côté et al., 2014). Together, these findings suggest that each age group can capitalise on their respective strength in memory consolidation and prior knowledge to support word learning. However, whether this difference reflects a developmental progression of increased dependence on prior knowledge or whether different age groups require different types of semantic support for lexical learning cannot be determined from the present results. A systematic investigation of intermediate ages, including adolescents, or using longitudinal methods, would provide better insights into how the developmental pattern observed here evolves.

Nevertheless, the developmental difference in the use of prior knowledge to support lexical learning we observed emerged under a specific type of semantic learning, which involved explicit word-picture pairings and minimal contextual information and instructions. Whilst pictures provided semantic information, participants were not instructed explicitly to make connections with prior knowledge in Experiments 3 to 5. While a picture description task was included in Experiments 1 and 2, which asked participants to describe one feature they noticed, participants were not prompted to make comparisons with familiar animals. Developmental studies demonstrated that children are capable of using prior knowledge when provided greater scaffolding and repeated exposures, such as through shared book reading and encountering novel words across multiple contexts (Hadley et al., 2019; Henderson & James, 2018; Horst et al., 2011). During shared book reading, for instance, including adult-guided discussions on taxonomic links with prior knowledge (e.g. radish is a type of vegetable) supported greater growth in preschool children's semantic knowledge (Hadley et al., 2019). By contrast, the present findings suggest that children do not spontaneously benefit from more accessible semantic links without explicit prompting during word learning; the questions remain about the age at which children might start to effectively utilise prior knowledge independently, without explicit instruction or scaffolding.

5.7 Individual differences in the role of "global" linguistic systems

The preceding sections discussed developmental differences in memory consolidation and semantic support mechanisms. A complementary approach to understanding the contribution of these two factors to word learning is through examining individual differences within each age group. Individual differences in "global" linguistic abilities, including vocabulary, phonological and literacy skills, provide a broad measure of the language systems that support new word encoding and consolidation, in adults and children with varying levels of underlying language ability. In this thesis, individual differences were examined in children in Experiments 1 and 3, focusing on the role of vocabulary knowledge and exploring the contribution of phonological skills - specifically phonological short-term memory - through nonword repetition. For adults, individual differences of vocabulary were examined in Experiments 4 and 5, with Experiment 5 also featuring a broader range of language and literacy skills. The following section will first focus on observation of the roles of vocabulary and phonological skills in children's word learning, before examining whether this pattern holds in adults.

Across Experiments 1 and 3, vocabulary was a consistent predictor of children's new word recall, demonstrating that both receptive and expressive vocabulary measures (the BPVS and WASI vocabulary tasks, respectively) predicted children's test performances across tasks. Vocabulary knowledge reflects the amount of semantic knowledge available that could support new word learning. However, vocabulary also indexes other linguistic skills that contribute to word learning. Children with a larger vocabulary are more likely to have a better specified phonological system that supports more effective encoding (Perfetti, 2007). The lexical restructuring hypothesis (Metsala & Walley, 1998) proposes that vocabulary growth drives increased phonological specificity to support better discrimination of similar-sounding words. Furthermore, expressive vocabulary, which was measured through a definition generation task, draws on other linguistic skills such as syntax, in addition to vocabulary knowledge (Wise et al., 2007). Thus, while vocabulary primarily reflects semantic knowledge, its role as a predictor of word learning likely draws on other interconnected linguistic skills.

Vocabulary knowledge has long been recognised as a predictor of novel word learning, with individual differences contributing to the widening of vocabulary and achievement gaps underscored by the "Matthew Effect", wherein "the rich get richer" (Cain & Oakhill, 2011; Stanovich, 1986). A key research question here is whether vocabulary advantages contribute as a general vocabulary learning mechanism or specifically through overnight consolidation processes. Prior studies suggested a consolidation-specific advantage, as children with a larger vocabulary showed more substantial overnight consolidation (Henderson et al., 2015; James et al., 2017). However, the present findings across Experiments 1 and 3 point to a more general vocabulary benefit, more consistent with the view that children with better vocabulary skills are better "language learners" who are more ready to establish new lexical representations.

Vocabulary appears to play a smaller role in adults' word learning capability, showing a less consistent pattern than children's vocabulary. In Experiments 4 and 5, expressive vocabulary did not predict performance in either word-form recall or picture naming in Experiment 4, but only predicted picture naming in Experiment 5. Sampling differences could contribute to the difference in word recall patterns, as Experiment 4 used a university-based sample, which had a high mean vocabulary score and relatively little variability. A more diverse sample was recruited for Experiment 5, including participants who received a diagnosis of dyslexia or suspected they had dyslexia, resulting in a wider range of vocabulary skills. Within this more diverse sample, expressive vocabulary predicted overall picture naming performance, suggesting that while vocabulary may have a smaller role in word learning outcome in adulthood than in childhood, in the sense that it no longer predicts word form recall, adults still draw on vocabulary knowledge when the recall task demands semantic retrieval.

Beyond vocabulary, phonological skills, assessed through nonword repetition tests, also predicted children's word learning. The exploratory analysis in Experiment 1 revealed that nonword repetition predicted children's overall word recall performance and improvements in word form recall across the one-day (but not one-week) consolidation period. The nonword repetition task draws on multiple phonological abilities, including phonological short-term memory capacity (Gathercole & Baddeley, 1989) and the precision of phonological representations (Metsala & Walley, 1998). This precision is relevant for both encoding and consolidation: precise initial phonological representations provide a stronger basis for consolidation into high-quality representations. Individuals with phonological weakness, therefore, face double disadvantages in both weaker initial encoding and less precise long-term representations. For adults in Experiment 5, which did not include a one-day delay test, nonword repetition predicted overall word form recall performance, but was not associated with changes across the one-week delay. Literacy skills (nonword decoding and spelling) also predicted overall performance, likely reflecting the phonology-orthography link that underpins lexical representations (Perfetti, 2007); but again, these did not predict changes in performance over one week. These findings underscore that the effects of phonological weaknesses on establishing long-term lexical representation continue to impact adults' word learning.

Phonological weaknesses are often quite specific, as in the case of dyslexia, where semantic skills are usually preserved. It is possible that in these individuals, semantic skills could compensate for the weaker encoding associated with the phonological weakness and contribute more during word learning. Prior studies on familiar word processing have suggested that individuals with weaker phonology tend to show greater reliance on the lexical-semantic pathway when temporarily memorising familiar and unfamiliar phonological sequences (Savill et al., 2019; van der Kleij et al., 2019). If semantic compensation can support word learning, then individuals with poorer nonword repetition would be expected to show a greater benefit from semantics than those with stronger phonological skills. However, neither children (Experiment 1) nor adults (Experiment 5) with lower nonword repetition performance demonstrated this pattern. This null finding suggests that semantic compensation observed in previous studies may depend on having pre-existing lexical-semantic representations of familiar words to support phonological and semantic retrieval processes. Savill et al. (2019) used immediate serial recall of lists mixing familiar words with nonwords, arguably allowing participants to leverage the semantic knowledge of familiar words to support the retention of the whole sequence. In contrast, the present experiments required participants to establish new phonological and semantic representations, providing no pre-existing memory traces to activate the compensatory mechanism. This suggests that the semantic compensatory mechanism might be limited to the retrieval of specific familiarised associations rather than generalised to developing new lexical-semantic representations efficiently.

5.8 Limitations & Outstanding questions

Some specific limitations to particular experiments or issues have been addressed in previous sections of this discussion and in the rest of the thesis. The following section will focus on key limitations that need addressing to further our understanding of developmental and individual differences in the timecourse of semantic and consolidation mechanisms in adults and children.

The experiments included in this thesis examined word learning using a behavioural approach and measured changes in recall performance at different timepoints. This approach allowed us to assess consolidation across broader contexts, including classroom-based group testing (Experiments 3 and 4) and the inclusion of a non-university sample with adults who have weaker literacy skills through online testing, enabling better generalisability. At the same time, we relinquished control over participants' activities between test sessions, such as subsequent learning that occurs across the rest of the school day, or emotionally salient events that might take place after word learning (Liu et al., 2008). We also cannot isolate whether changes across test sessions reflected differences in consolidation that took place during sleep, quiet rest or other memory-enhancing activities such as rehearsing. Further insights into the activities during these interim periods through measures such as actigraphy, experience sampling, or even polysomnography would provide qualitative data from a smaller sample to enrich the current interpretation.

As discussed above (Section 5.6), apart from the picture description task in Experiments 1 and 2, the other learning tasks directed participants' attention to the word forms through repetition and word-picture association in matching tasks. This behavioural design limits the insight into how much of the semantic features within the pictures were considered during learning, for instance, using taxonomic information and creating associations with superordinate categories or focusing on the uniqueness of each stimulus. While a description task, as used in Experiments 1 and 2, could provide insight into the strategy used by each participant, this task also directs participants to use a semantic strategy in their learning and draws attention away from the word forms (Hawkins & Rastle, 2016). Without direct measures of online semantic processing, it is unclear whether children's minimal semantic differentiation reflects the failure to leverage semantic connections effectively or a strategic prioritisation of alternative learning mechanisms. Both of these interpretations have different implications for educational practice. For instance, if children can detect semantic connections – as indicated by the semantic benefits in the definition recall task – but fail to use them strategically to support learning, this would point to exploring explicit scaffolding or instructions to use semantic information, and perhaps suggesting that the metacognitive skills required to utilise relevant prior knowledge may still be developing. In contrast, if children are prioritising phonological encoding over integrating all the relevant phonological and semantic information, then educational approaches should appeal to children's consolidation strength and explore introducing different sources of information in stages.

One of the developmental assumptions underlying the research questions is that a more mature semantic system should lead to greater semantic benefits. Adults, who have larger vocabularies and a well-developed semantic network, should be more adept at using prior knowledge than children. However, semantic benefits could also depend on specific relevant knowledge; for example, familiarity with animals likely varies among individuals, especially among children who have specialised focused interests (Arunachalam et al., 2024) and having this rich understanding of animals might benefit the learning of the novel animal stimuli used in this thesis. Assessing individual domain knowledge, such as through an animal knowledge quiz, could potentially clarify whether the general richness of semantic knowledge or expertise knowledge of relevant domains is the main driver of semantic benefits. Future research could explore whether tailoring semantic manipulations to children's and adults' prior knowledge can allow them to use their prior knowledge more effectively. More broadly, the present findings are constrained by the specificity of this experimental paradigm. Semantic associations were manipulated through resemblance to familiar animals alone, meaning all stimuli were presented as animate items. Since animacy is known to enhance word learning (Laurino & Kaczer, 2019), the observed effects may not generalise to learning words of inanimate objects or from other word classes. The minimal explicit semantic instructions within a single learning session also deviate from typical classroom vocabulary teaching, where new words are introduced gradually across multiple sessions (Gordon & Grieco-Calub, 2024). The findings here focused on word-picture pair associations under a constrained semantic manipulation, which may not generalise to vocabulary development under a richer and more dynamic learning environment.

5.9 Implications

One important educational implication from the current thesis arises from the encouraging finding that children demonstrated robust offline consolidation regardless of initial levels of learning or pre-existing vocabulary abilities. Even among children with lower vocabulary abilities, who showed lower initial levels of learning, demonstrated substantial improvement in word recall in the week following learning. This suggests that consolidation mechanisms remain intact in these learners and can support vocabulary acquisition when given sufficient time. Educators should recognise that vocabulary learning extends well beyond classroom instruction, with the current results showing continued improvements following multiple offline consolidation opportunities. Including tests and retrieval opportunities in the subsequent day after offline consolidation also showed some promising long-term benefits that could inform the assessment and revision schedules, although these exploratory patterns require more systematic examination and replication.

At the same time, identifying specific points of weakness that lead to poorer vocabulary learning remains a major challenge. Across all the experiments reported here, vocabulary ability consistently predicted overall word learning performance, without interacting with the semantic manipulations or consolidation processes in ways that can be targets for interventions. Children with poorer vocabulary appear to be less efficient word learners, but the current results suggest that they are not particularly compromised in terms of using semantics or relying on consolidation than their peers. Exploratory analysis in Experiment 1 provided some evidence that children with phonological short-term memory could be a promotive factor (Slomowitz et al., 2021) for consolidation, such that children with stronger nonword repetition benefitted from larger overnight consolidation in addition to better overall learning. Although current results do not appear to suggest that children with weaker phonological short-term memory showed significant forgetting, further research is needed to clarify whether their weaker consolidation is a by-product of weaker encoding or an additional vulnerability.

The central theoretical contribution of this work focuses on the role of prior knowledge in vocabulary learning, and specifically, *when* prior knowledge exerts its influence. The present findings consistently demonstrate that support from prior knowledge and memory consolidation operate as independent mechanisms: prior knowledge benefits were apparent during immediate testing and persisted across consolidation opportunities without further strengthening. This pattern is consistent with the proposal that schema-consistency allows for rapid assimilation (McClelland, 2013; Tse et al., 2007), rather than facilitating integration during hippocampal reactivation (Lewis & Durrant, 2011). Offline consolidation processes strengthen all newly learned lexical representations, regardless of whether they received weak or strong support from prior knowledge.

The second key theoretical contribution of this work lies in demonstrating a difference in the relative importance of learning mechanisms across development. Children consistently showed larger consolidation gains than adults across one-week delays; this developmental difference was also observed after a one-day delay, which included an offline consolidation opportunity, but was not observed after a brief daytime rest. This suggests that children's superior consolidation is driven by active, sleep-dependent processes, which are related to developmental differences in sleep architecture (Wilhelm et al., 2012), rather than a more general role for passive protection and stabilisation, which temporarily maintains the novel representations. In contrast, adults showed greater reliance on prior knowledge to support word learning, as their semantic benefits emerged at immediate test and most strongly in tasks tapping semantic retrieval. This developmental difference also has important implications for theoretical models of memory and vocabulary learning, which currently do not account for changes in the relative importance of hippocampal consolidation and neocortical integration mechanisms across development. Theoretical refinement of these models should incorporate the physiological changes in sleep architecture over the course of development, as well as the maturation of semantic networks and language processing skills that enable prior knowledge to be recruited during learning.

5.10 Conclusion

Vocabulary development is the foundation for a broad range of skills throughout development and a key focus of early and primary education. A crucial motivation for this research is to understand factors underlying word learning differences that might inform interventions for struggling learners. The studies presented in this thesis focused on the questions of *when* and for *whom* prior knowledge benefits vocabulary learning, seeking to understand the timecourse over which semantic information may enhance the learning and consolidation of new words. In addition, this work aimed to characterise the developmental and individual differences in these patterns of learning and consolidation.

The evidence demonstrates that when "local" semantic connections with prior knowledge benefit word form learning in adults, they provide immediate support for new lexical representations. However, children do not appear to utilise these semantic links automatically to support word form learning. Instead, children benefit from enhanced offline consolidation gains, which emerge following a single and multiple overnight consolidation opportunities. For both children and adults, establishing new lexical representations is heavily dependent upon existing "global" linguistics and vocabulary skills. Characterising these developmental and individual differences in the timecourse of word learning is key to theoretical refinements which incorporate developmental perspectives into models of vocabulary learning.

Appendices

Appendix A Stimuli Rating Pilot Experiments

Thirty-seven animal stimuli were created initially, and two pilot studies were implemented to select items to be included in the word learning study. First, a *naming pilot study* was conducted with 15 adults and 10 children aged 8 to 12 years online using the Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). Participants were asked to indicate if they recognized the animal depicted in the picture by pressing one of the three buttons: "yes", "no", or "not sure". They were then asked to type any other animals that each animal stimulus reminded them of (children were recommended to ask an adult for assistance if needed) and to rate the similarity of each one to the named animals on a 5-point Likert scale. They were also asked to rate their familiarity with the animal on a 5-point Likert scale to indicate whether they thought the animal stimuli were common or unusual.

Second, a *feature listing pilot study* was conducted with another 16 adult participants online using the Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). For each picture, participants listed animals the picture reminded them of, followed by listing distinctive visual features, such as any unusual body parts, size, shape or colour. Together, eight stimuli from each condition that fit the selection criteria were selected for the main experiment. Stimuli for the Highly Linkable condition were selected for the word learning study if they were 1) recognized by a majority of participants (less than 5 adults and 5 children indicating they do not recognise the animal) in the naming pilot study; 2) linkable with familiar animals, such that less than 3 adults or 3 children indicated that the particular stimuli could not remind them of any familiar animals; and 3) consistency in naming, such that each selected animal stimulus consistently reminded participant of the same 1 or 2 familiar animals (e.g. 23 out of 25 participants responded that a pipa reminded them of a frog).

Less Linkable stimuli were selected if the stimulus had 1) a lower recognition rate, such that more than half of the participants indicated that they did not recognise the animal or were not sure; and 2) no consistent link between these items and any common animals, which was quantified by less than half of the participants responding with the same familiar animal in the picture naming pilot study.

Appendix Table A.1 Summary statistics from the naming pilot study for the selected stimuli in the highly linkable and less linkable conditions

	Adult pilot (n=15)			Child pilot (n=10)		
	Recognition Rate (SD)	Familiarity Rating* (SD)	Similarity Rating (SD)^	Recognition Rate (SD)	Familiarity Rating* (SD)	Similarity Rating (SD)^
Highly Linkable	.82 (.08)	2.7 (.40)	3.09 (.46)	.66 (.11)	2.79 (.45)	3.15 (.37)
Less Linkable	.33 (.09)	1.56 (.30)	1.83 (.22)	.13 (.08)	1.58 (.27)	1.86 (.37)

*Familiarity rating was collected out of a 5-point Likert scale, with 1 being very unfamiliar and 5 being highly familiar.

^Similarity rating used a 5-point Likert scale. Participants were asked to score the degree to which an animal stimulus pictured matched what they thought the animal they named should look like, with 1 being very dissimilar and 5 being very similar.

Appendix Figure A-1 List of Stimuli used in all Experiments (Rows 1 and 2: Highly Linkable Condition; Rows 3 and 4: Less Linkable Condition)

Appendix B Exploratory analysis examining relationships between phonological working memory (nonword repetition) and word learning for Experiment 1

We pre-registered an exploratory analysis for the phonological cued recall task using scaled scores from the nonword repetition (NWR) subtest. Similar to the receptive vocabulary analysis, we predicted better word learning performance in children with better NWR (Jackson et al., 2020); however, there is insufficient evidence from existing literature to support a hypothesis on NWR predicting changes across test sessions or differences between semantic conditions. The scaled scores for the NWR test and the standardised scores of the BPVS were highly correlated (r = .69, p <.001); they were not included in the same analysis due to multicollinearity. In this exploratory analysis, centred scaled scores for the NWR test were included as a predictor alongside the same fixed effect contrasts and interactions of test sessions and semantic conditions for phonological cued recall performance. For completeness, we also conducted exploratory analyses using centred scaled scores for the NWR test as a predictor for the picture naming and definition recall tasks, which were not pre-registered.

Similar to the main analyses with BPVS as a predictor, children with a higher NWR score demonstrated higher accuracy in all three tasks (Phonological cued recall: β = .07, SE = .03, z = 2.07, p =.038; Picture Naming: β = .20, SE = .05, z = 3.73, p <.001; Definitions Recall: β = .14, SE = .04, z = 3.94, p =.001, Appendix Table B.1 to B.3). For phonological cued recall, we also found an interaction between the changes across a 1-day delay and NWR scores (β = .10, SE = .04, z = 2.21, p =.027): children with better nonword repetition showed greater improvement from immediate to 1-day delay test. Furthermore, there was also a significant interaction between Session2-1 and semantics2 (β = .33, SE = .16, z = 2.08, p =.038). Post-hoc comparisons showed a greater improvement in the Less Linkable condition than the Highly Linkable condition across the immediate and 1-day delay tests.

Unlike phonological cued recall, there was no significant interaction between the picture naming accuracy changes across test sessions and NWR scores across test sessions (ps >.2). Rather, a significant interaction between semantic conditions and improvements across 1 week (*Session3-2*Semantics2:* β = .38, SE = .18, z = 2.13, p = .033). Post-hoc comparisons suggested that this was driven by a greater improvement in accuracy from T2 to T3 for the Less Linkable condition (T2: mean = .10, SD = .30, T3: mean = .15, SD = .35,

Figure 3) than the Highly Linkable condition (T2: mean = .12, *SD* = .33, T3: mean = .15, *SD* = .36, Figure 3).

Using NWR scores as a predictor of definition task performance yielded similar findings as the pre-registered model using BPVS scores (Appendix Table B.3). NWR scores predicted overall accuracy of the definition recall task ($\beta = .14$, $SE = .04$, $z = 3.94$, $p < .001$), but there was no significant interaction between NWR scores with changes across test sessions (*p*s > .4) nor between NWR scores and semantic conditions (*p*s> .08).

Appendix Table B.1 Predictors of Children's Phonological Cued Recall Performance with Nonword Repetition for Experiment 1

Fixed effects:	b	SE	z	p	
(Intercept)	-2.24	.25	-9.07	<.001	***
Session2-1	1.04	.14	7.30	<.001	***
Session3-2	.83	.11	7.61	<.001	***
Semantics1	-.18	.10	-1.93	.053	.
Semantics2	-.13	.25	-.50	.617	
Nonword Repetition	.07	.03	2.07	.038	*
Session2-1:Semantics1	.12	.11	1.10	.274	
Session3-2:Semantics1	-.05	.08	-.58	.560	
Session2-1:Semantics2	.33	.16	2.08	.038	*
Session3-2:Semantics2	.03	.13	.26	.797	
Session2-1:Nonword Repetition	.10	.04	2.21	.027	*
Session3-2:Nonword Repetition	.03	.03	.85	.397	
Semantics1:Nonword Repetition	-.01	.02	-.41	.680	
Semantics2:Nonword Repetition	-.03	.03	-1.00	.318	
Session2-1:Semantics1:Nonword Repetition	.03	.03	.91	.365	
Session3-2:Semantics1:Nonword Repetition	-.01	.02	-.37	.712	
Session2-1:Semantics2:Nonword Repetition	.04	.05	.70	.481	
Session3-2:Semantics2:Nonword Repetition	-.01	.04	-.30	.762	

Random effects	Variance	SD
Participant: (intercept)	.47	.69
Participant: Semantics1 (slope)	.06	.24
Participant: Semantics2 (slope)	.23	.48

Target: (intercept)	1.15	1.07

* p<.05, ** p<.005, *** p<.001

Note: model from 4020 observations collected from 57 participants across 24 items, after removing the data from 4 influential participants

Appendix Table B.2 Predictors of Children's Picture Naming with Nonword Repetition for Experiment 1

Fixed effects:	b	SE	z	p	
(Intercept)	-3.05	.30	-10.09	<.001	***
Session2-1	.74	.18	4.14	<.001	***
Session3-2	.46	.14	3.18	.001	**
Semantics1	-.01	.05	-.22	.824	
Semantics2	-.09	.08	-1.17	.243	
Nonword Repetition	.20	.05	3.73	<.001	***
Session2-1:Semantics1	.18	.13	1.37	.170	
Session3-2:Semantics1	-.09	.10	-.87	.385	
Session2-1:Semantics2	-.05	.22	-.22	.824	
Session3-2:Semantics2	.38	.18	2.13	.033	*
Session2-1:Nonword Repetition	-.03	.06	-.53	.597	
Session3-2:Nonword Repetition	-.03	.05	-.56	.573	
Semantics1:Nonword Repetition	.02	.02	1.06	.290	
Semantics2:Nonword Repetition	.00	.03	-.05	.962	
Session2-1:Semantics1:Nonword Repetition	-.05	.05	-1.08	.280	
Session3-2:Semantics1:Nonword Repetition	.04	.03	1.29	.197	
Session2-1:Semantics2:Nonword Repetition	-.04	.07	-.57	.567	
Session3-2:Semantics2:Nonword Repetition	-.06	.06	-1.02	.310	

Random effects	Variance	SD
Participant: (intercept)	1.17	1.08
Target: (intercept)	1.42	1.19

* p<.05, ** p<.005, *** p<.001

Note: model from 3738 observations collected from 53 participants across 24 items, after removing the data from 8 influential participants

Appendix Table B.3 Predictors of Children's Definitions Recall with Nonword Repetition for Experiment 1

Fixed effects:	b	SE	z	p	
(Intercept)	-2.23	.22	-10.3	<.001	***
Session2-1	.03	.13	.21	.836	
Session3-2	.11	.13	.88	.377	
Semantics1	-.69	.13	-5.18	<.001	***
Semantics2	-.25	.20	-1.28	.202	
Nonword Repetition	.14	.04	3.94	<.001	***
Session2-1:Semantics1	-.12	.10	-1.15	.250	
Session3-2:Semantics1	.01	.10	.08	.940	
Session2-1:Semantics2	.15	.13	1.16	.244	
Session3-2:Semantics2	-.08	.13	-.60	.550	
Session2-1:Nonword Repetition	.01	.04	.15	.884	
Session3-2:Nonword Repetition	.02	.04	.48	.630	
Semantics1:Nonword Repetition	.02	.03	.63	.532	
Semantics2:Nonword Repetition	-.04	.02	-1.76	.079	
Session2-1:Semantics1:Nonword Repetition	.00	.03	-.12	.906	
Session3-2:Semantics1:Nonword Repetition	-.02	.03	-.59	.558	
Session2-1:Semantics2:Nonword Repetition	-.03	.04	-.77	.439	
Session3-2:Semantics2:Nonword Repetition	.03	.04	.81	.420	

Random effects	Variance	SD
Participant: (intercept)	.58	.76
Participant: Semantics1 (slope)	.40	.63
Participant: Semantics2 (slope)	.22	.47

Target: (intercept)	.66	.81

* p<.05, ** p<.005, *** p<.001

Note: model from 4161 observations collected from 59 participants across 24 items, after removing the data from 2 influential participants

Appendix C Exploratory analyses examining developmental differences in picture naming and definition recall task for Experiments 1 and 2

Appendix Table C.1 Predictors of Developmental Differences in Picture Naming for Experiments 1 & 2

Fixed effects	b	SE	z	p	
(Intercept)	-2.19	.24	-9.14	<.001	***
Session2-1	1.05	.15	7.10	<.001	***
Session3-2	.81	.11	7.39	<.001	***
Semantics1	-.20	.09	-2.36	.018	*
Semantics2	-.21	.23	-.90	.371	
Age Group	.25	.27	.94	.350	
Session2-1:Semantics1	.07	.11	.64	.521	
Session3-2:Semantics1	-.04	.08	-.54	.591	
Session2-1:Semantics2	.47	.17	2.74	.006	**
Session3-2:Semantics2	.09	.13	.70	.486	
Session2-1:Age Group	-.31	.30	-1.04	.299	
Session3-2:Age Group	-.01	.23	-.06	.952	
Semantics1:Age Group	-.24	.10	-2.43	.015	*
Semantics2:Age Group	-.09	.20	-.45	.650	
Session2-1:Semantics1:Age Group	.16	.23	.71	.479	
Session3-2:Semantics1:Age Group	-.07	.16	-.41	.684	
Session2-1:Semantics2:Age Group	-.36	.34	-1.04	.299	
Session3-2:Semantics2:Age Group	-.13	.27	-.50	.617	

Random effects	Variance	SD
Participant: (intercept)	2.19	1.48

Participant: Semantics1 (slope)	.11	.33
Participant: Semantics2 (slope)	.14	.38
Target: (intercept)	1.17	1.08

* p<.05, ** p<.005, *** p<.001

Note: model from 8178 observations collected from 115 participants across 24 items, after removing the data from 9 influential participants

Appendix Table C.2 Predictors of Developmental Differences in Definition Recall for Experiments 1 & 2

Fixed effects	b	SE	z	p	
(Intercept)	-3.06	.25	-12.20	<.001	***
Session2-1	.03	.18	.16	.874	
Session3-2	-.03	.19	-.17	.867	
Semantics1	-1.33	.17	-7.69	<.001	***
Semantics2	-.40	.19	-2.07	.039	*
Age Group	-.85	.17	-5.11	<.001	***
Session2-1:Semantics1	-.15	.17	-.90	.366	
Session3-2:Semantics1	.00	.18	-.01	.995	
Session2-1:Semantics2	.21	.10	2.15	.032	*
Session3-2:Semantics2	-.04	.09	-.44	.659	
Session2-1:Age Group	-.08	.18	-.47	.638	
Session3-2:Age Group	-.06	.19	-.31	.761	
Semantics1:Age Group	-.63	.13	-4.86	<.001	***
Semantics2:Age Group	-.14	.09	-1.48	.139	
Session2-1:Semantics1:Age Group	-.05	.17	-.28	.778	
Session3-2:Semantics1:Age Group	.05	.18	.25	.800	
Session2-1:Semantics2:Age Group	-.03	.10	-.29	.775	
Session3-2:Semantics2:Age Group	.03	.09	.35	.729	

Random effects	Variance	SD
Participant: (intercept)	1.04	1.02
Participant: Semantics1 (slope)	.43	.66
Participant: Semantics2 (slope)	.25	.50

Target: (intercept)	.71	.84
Target: Age Group (slope)	.10	.31

* p<.05, ** p<.005, *** p<.001

Note: model from 8099 observations collected from 114 participants across 24 items, after removing the data from 10 influential participants

Appendix D Exploratory analysis on Age Differences in Children's Phonological Cued Recall for Experiment 1

Appendix Table D.1 Predictors of Age Differences in Children's Phonological Cued Recall for Experiment 1

Fixed effects	b	SE	z	p	
(Intercept)	-2.19	.24	-9.14	<.001	***
Session2-1	1.05	.15	7.10	<.001	***
Session3-2	.81	.11	7.39	<.001	***
Semantics1	-.20	.09	-2.36	.018	*
Semantics2	-.21	.23	-.90	.371	
Age	.25	.27	.94	.350	
Session2-1:Semantics1	.07	.11	.64	.521	
Session3-2:Semantics1	-.04	.08	-.54	.591	
Session2-1:Semantics2	.47	.17	2.74	.006	**
Session3-2:Semantics2	.09	.13	.70	.486	
Session2-1:Age	-.31	.30	-1.04	.299	
Session3-2:Age	-.01	.23	-.06	.952	
Semantics1:Age	-.24	.10	-2.43	.015	*
Semantics2:Age	-.09	.20	-.45	.650	
Session2-1:Semantics1:Age	.16	.23	.71	.479	
Session3-2:Semantics1:Age	-.07	.16	-.41	.684	
Session2-1:Semantics2:Age	-.36	.34	-1.04	.299	
Session3-2:Semantics2:Age	-.13	.27	-.50	.617	

Random effects	Variance	SD
Participant: (intercept)	.45	.67
Target: (intercept)	1.07	1.03
Target: Age Group (slope)	.45	.67

* p<.05, ** p<.005, *** p<.001

Note: model from 3801 observations collected from 54 participants across 24 items, after removing the data from 7 influential participants

Appendix E Exploratory analysis of the role of self-reported frequency of rehearsal during the retention period on orthographic cued recall accuracy for Experiments 3 and 4

Exploratory analysis also examined if participants' self-reported frequency of thinking about the words predicted performance in post-retention and in one-week delay tests. Separate generalised linear mixed effects models were fitted for post-retention and one-week delay test accuracy in the orthographic cued recall task, with the immediate test accuracy as a continuous fixed effect, retention conditions as a fixed effect and self-reported rehearsal frequency as a categorical fixed effect with Helmert contrasts. The first contrast compared participants reporting not thinking about the words at all and those who did, regardless of frequency, while the second contrast compared thinking about the words "once or twice" and "a few times or more".

The best-fitted model revealed that children's self-report of thinking about the words, compared to not thinking about the words at all, had a significant positive effect on post-test accuracy (β = .53, *SE* = .22, *z* = 2.41, *p* =.016). This effect is qualified by a significant interaction with pre-test accuracy (β = -.43, *SE* = 0.21, *z* = -2.07, *p* =.038), such that there is a bigger benefit of rehearsal on post-retention test accuracy among children with lower pre-retention test performance. However, whether children were thinking about the words briefly or extensively did not impact longer-term performance at the one-week delay test (*p*s > .137). Furthermore, there was no evidence for a greater rehearsal benefit for wakeful rest than for active wake, either at the post-test (*p = .265)* or at the one-week delay test (*p* = .509). For adults, thinking about the words during the retention period did not affect their orthographic cued recall accuracy at post-retention or at one-week delay tests (*p*s> .14).

Further exploratory analysis, which was not pre-registered, was also conducted to examine whether children are more likely to rehearse the words than adults during the retention period, potentially explaining the better orthographic cued recall outcome after a one-week delay for children. A chi-square test comparing self-reported frequency of thinking about the words showed significant differences across age groups (χ^2(2, N = 255) = 12.44, *p* = .002). 47.9 % of adults (58/121) and 53.0% of children (71/134) did not think about the words during the retention period. However, among those who reported thinking about the words, adults were more likely to report thinking about the words once or twice (38.0% or

46/121) than thinking about it a few times or more (14.0% or 17/121); whereas children were more likely to report thinking about the words more frequently ("a few times or more", 26.9% or 36/134) than only once or twice (20.1% or 27/134). Standardised residuals suggest that this significant effect is mostly driven by more adults thinking about the words once or twice than expected values based on a null distribution (standardised residuals = 1.93), and children reported thinking about the words "once or twice" less than expected values (standardised residuals = -1.83). This could potentially highlight differences in internal activities by adults and children. Nonetheless, when examining the effects of this difference in rehearsal between age groups on orthographic cued recall outcomes, the generalised linear mixed effects model showed that the interaction between age groups and rehearsal frequency was not a significant predictor of cued recall accuracy (ps> .10).

Appendix F Exploratory post-hoc Bayesian analyses on wakeful rest effects in Experiments 3 and 4

Exploratory post-hoc Bayesian analyses were conducted to examine the extent to which our non-significant results for retention conditions in the pre-registered analyses supported the null hypotheses. Bayesian mixed-effects models using the brms (Bayesian regression models using 'Stan') package (Bürkner, 2017) with the same fixed and random effect structures as the frequentist counterparts, using a Bernoulli distribution and a weakly informative prior following Ricketts et al. (2021). For the main effects of retention condition, directional Bayesian hypothesis tests were conducted for the alternative hypothesis of the Wakeful Rest condition performing better than the Active Wake condition. The following tables summarise the posterior distributions for each task, and we report each estimate and 95% credible intervals. A credibility interval that crosses 0 indicates less certainty of the direction and size of the effect.

For children's orthographic cued recall, the posterior mean for the retention condition was b = -.30 (95% credibility interval (CrI): [-.63, .03]). A directional Bayesian hypothesis test (BF10 = .04) provided strong evidence in favour of the null hypothesis and against a wakeful rest advantage. For changes across test sessions, there were anecdotal evidence for no improvement from pre- to post-retention test (BF10 = .66, b = -.04, 95% CrI = [-.33, .26]), but very strong evidence for improvements in recall accuracy between Post- to Delay Test (BF10 = 62.16, b = .30, 95% CrI = [.03, .58]). These Bayesian results mirrored the frequentist mixed-effects models reported in Experiment 3, converging on the conclusion that there is no evidence of a wakeful rest benefit compared to active wake following word learning in a classroom setting.

For children's picture naming, a directional Bayesian hypothesis test provided strong evidence for the null hypothesis (BF10 = .03, b = -.47, 95% CrI = [-.96, .03]), suggesting that there were no wakeful rest benefits. For changes across test sessions, there were moderate evidence for no improvement from Pre to Post Test (BF10 = .05, b = -.25, 95% CrI = [-.54, .05]), as well as moderate evidence for no improvement between Post to Delay Test (BF10 = .20, b = -.16, 95% CrI = [-.51, .19]).

In adults' orthographic cued recall, the posterior estimates for retention condition were b = -.01 (95% CrI = [-.47, .45]), a directional Bayesian hypothesis test (BF10 = .95) provided no evidence that wakeful rest exceeded active wake condition. For test sessions, there are moderate evidence for no change in performance between pre- and post-retention tests (BF10 = .20, *b* = -.09, 95% CrI = [-.45, .26]) and weak evidence for no change in performance between post-retention and one-week delay tests (BF10 = .45, *b* = -.23, 95% CrI = [-.55, .10]).

In adults' picture naming, the posterior estimates for retention condition were *b* = -.01 (95% CrI = [-.70, .50]), a directional Bayesian hypothesis test (BF10 = .59) provided weak evidence against wakeful rest exceeding active wake condition. For test sessions, there are weak evidence for no change in performance between pre- and post-retention tests (BF10 = .37, *b* = -.07, 95% CrI = [-.29, .15]) and extreme evidence for forgetting following the one-week delay (BF10 = 412.79, *b* = -.32, 95% CrI = [-.55, .10]).

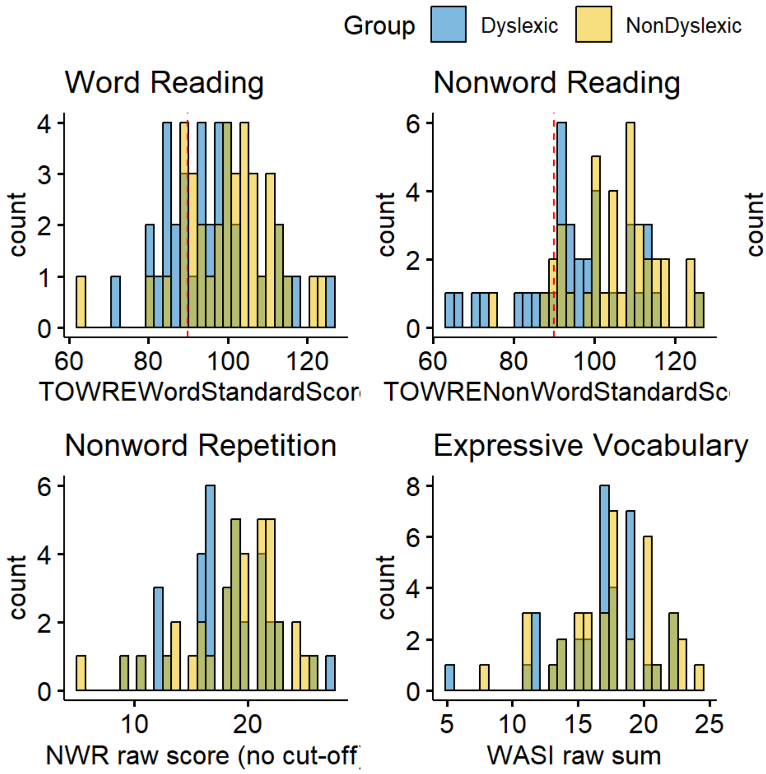
In summary, across two tasks in both adults and children, Bayesian mixed models consistently yielded Bayes factors between .03 and .95 for retention conditions, indicating that the data were more consistent with the null hypothesis of no wakeful rest benefit.

Appendix G Background measures and Standardised Tests for Experiment 5

Appendix Table G.1 Mean score for all background measures

Measure	Test	Dyslexic Group (N = 36)				Non-Dyslexic Group (N = 41)				F, p-values
		raw score		standard score		raw score		standard score		
		mean (SD)	range	mean (SD)	range	mean (SD)	range	mean (SD)	range	
Adult Reading Questionnaire[1]		18.54 (6.22)	8 - 28	-	-	10.59 (3.73)	2 - 19	-	-	54.93, p <.001
Nonword Repetition[2]	CToPP-2	18.05 (3.95)	9 - 27	-	-	18.73 (4.49)	5 - 26	-	-	.72, p = .396
Expressive Vocabulary[2]	WASI-II	16.81 (3.47)	5 - 22	-	-	17.33 (3.91)	8 - 24	-	-	.91, p = .341
Word Reading[3]	TOWRE-2	84.47 (11.51)	54 - 107	95.39 (11.77)	72 - 127	88.75 (12.29)	48 - 106	99.65 (12.07)	64 - 124	3.23, p = .076
Nonword Reading[3]	TOWRE-2	45.19 (12.32)	15 - 65	95.89 (13.85)	64 - 126	52.73 (9.7)	25 - 65	104.78 (12.36)	73 - 126	10.04, p = .002
Spelling	WRAT	40.59 (5.44)	30 - 52	93.97 (14.07)	69 - 128	45.33 (4.79)	31 - 53	106.8 (12.92)	70 - 131	21.43, p <.001

Note: [1] *Maximum ARQ score is 43;* [2]*Due to changes to administration (see "Literacy and Language measures" below), the accuracy for vocabulary and nonword repetition was not converted to standard scores. The maximum score for vocabulary is 28 and for nonword repetition is 30;* [3]*Data missing from 1 participant in the dyslexic group due to recording issues.*



Appendix Figure G-1 Histogram of performance in each of the standardised measures by group

Appendix H Analysis using Bayesian Mixed-Effect Models for Experiment 5

Bayesian mixed-effects models were also fitted using *brms* (Bürkner, 2017) to supplement the outcomes of the frequentist model, and 95% credibility intervals were reported to supplement interpretation, as credibility interval indicates the range within which the "true value" of a parameter lies. For phonological cued recall, a Bernoulli distribution was used. As values of picture naming MP range from 0 to 1 inclusive, a zero-one-inflated Beta distribution was used. Bayes factor is also reported for hypothesis testing by comparing the full model and a reduced model for each fixed effect.

For phonological cued recall, the results from the Bayesian model (see Appendix Table H.1) were consistent with the frequentist model reported above, as the fixed effect of Session has a negative impact on the accuracy, indicating forgetting between Tests 1 and 2. Better literacy skills also support a higher probability of an accurate cued recall. Concurrent with the frequentist model reported above, the effects of semantics and other interaction terms on cued recall accuracy were less certain. Model comparison between the full model and a reduced model removing the semantics effect and its interactions indicated strong evidence against including Semantics (*BF10* = .00033), suggesting that Highly Linkable semantics do not significantly improve cued recall.

Appendix Table H.1 Bayesian mixed model summary for phonological form cued recall in Experiment 5

Effect	Estimate	Est. Error	95% Credible Interval	
			Lower Bound	Higher Bound
Intercept	-.83	.36	-1.55	-.12
SessionT2	-.51	.14	-.79	-.23
SemanticsHighly	.62	.50	-.37	1.61
Literacy	.70	.15	.42	.99
SessionT2:SemanticsHighly	-.09	.20	-.47	.30
SessionT2:Literacy	-.23	.16	-.56	.09

SemanticsHighly:Literacy	-.18	.15	-.48	.12
SessionT2:SemanticsHighly:Literacy	.05	.22	-.38	.48

Note: Literacy - Literacy skills composite of the standard scores of TOWRE-2 nonword reading and WRAT spelling

The results of the Bayesian mixed effects model for picture naming can be found in Appendix Table H.2. First of all, the changes across one week and the effects of literacy remained unchanged, as the Bayesian model also suggested a decrease in picture naming accuracy after one week, and performance was more accurate among participants with stronger literacy skills. Nevertheless, the Bayesian model suggests that there is no credible effect for semantics. Adults with better literacy skills also showed no credible greater forgetting after one week as per the Bayesian model, deviating from the frequentist results.

Appendix Table H.2 Bayesian mixed model summary for picture naming in Experiment 5

			95% Credible Interval	
Effect	Estimate	Est. Error	Lower Bound	Lower Bound
Intercept	-.21	.08	-.37	-.05
SessionT2	-.20	.08	-.36	-.05
SemanticsHighly	.08	.10	-.12	.28
Literacy	.26	.07	.12	.41
SessionT2:SemanticsHighly	-.11	.11	-.33	.11
SessionT2:Literacy	-.07	.09	-.24	.10
SemanticsHighly:Literacy	-.11	.09	-.29	.07
SessionT2:SemanticsHighly:Literacy	.17	.13	-.08	.42

Note: Literacy – Literacy skills composite of the standard scores of TOWRE-2 nonword reading and WRAT spelling

Appendix I Exploratory analyses examining the relationships between linguistic abilities and word learning for Experiment 5

Appendix Table I.1 Predictors of Adults' Phonological Cued Recall Performance with Expressive Vocabulary for Experiment 5

Fixed effects:	Estimates	SE	z	p	
(Intercept)	-.85	.31	-2.76	.006	**
SessionT2	-.50	.14	-3.58	<.001	***
SemanticsHighly	.60	.41	1.45	.148	
Vocabulary	.15	.13	1.16	.246	
SessionT2:SemanticsHighly	-.10	.19	-.50	.614	
SessionT2:Vocabulary	-.04	.14	-.31	.756	
SemanticsHighly:Vocabulary	.06	.13	.48	.630	
SessionT2:SemanticsHighly:Vocabulary	-.02	.19	-.10	.921	

Random effects	Variance	SD
Participant: (intercept)	.65	.80
Target: (intercept)	.61	.78

* p<.05, ** p<.005, *** p<.001

Appendix Table I.2 Predictors of Adults' Phonological Cued Recall Performance with Nonword Repetition for Experiment 5

Fixed effects:	Estimates	SE	z	p	
(Intercept)	-.82	.31	-2.65	.008	**
SessionT2	-.53	.14	-3.79	<.001	***
SemanticsHighly	.59	.41	1.44	.151	
Nonword Repetition	.27	.13	1.99	.046	*
SessionT2:SemanticsHighly	-.07	.19	-.39	.698	
SessionT2: Nonword Repetition	.03	.14	.24	.809	
SemanticsHighly: Nonword Repetition	-.04	.13	-.29	.773	
SessionT2:SemanticsHighly: Nonword Repetition	.02	.19	.10	.923	

Random effects	Variance	SD
Participant: (intercept)	.65	.81
Target: (intercept)	.62	.78

* p<.05, ** p<.005, *** p<.001

Appendix Table I.3 Predictors of Adults' Picture Naming Performance with Expressive Vocabulary for Experiment 5

Fixed effects:	Estimates	SE	df	z	p	
(Intercept)	.36	.04	31.85	9.78	<.001	***
SessionT2	-.12	.02	2336.00	-5.96	<.001	***
SemanticsHighly	.11	.04	17.22	2.49	.023	*
Vocabulary	.05	.02	131.60	1.97	.051	.
SessionT2:SemanticsHighly	-.05	.03	2336.00	-1.98	.048	*
SessionT2:Vocabulary	.02	.02	2336.00	.83	.404	
SemanticsHighly:Vocabulary	.02	.02	2336.00	1.12	.263	
SessionT2:SemanticsHighly:Vocabulary	.00	.03	2336.00	-.15	.882	

Random effects	Variance	SD
Participant: (intercept)	.03	.17
Target: (intercept)	.01	.08

* p<.05, ** p<.005, *** p<.001

Appendix Table I.4 Predictors of Adults' Picture Naming Performance with Nonword Repetition for Experiment 5

Fixed effects:	Estimates	SE	df	z	p	
(Intercept)	.36	.04	34.25	9.87	<.001	***
SessionT2	-.12	.02	2367.00	-6.05	<.001	***
SemanticsHighly	.11	.04	17.24	2.51	.022	*
Nonword Repetition	.06	.02	125.90	2.43	.017	*
SessionT2:SemanticsHighly	-.06	.03	2367.00	-2.03	.043	*
SessionT2: Nonword Repetition	-.02	.02	2367.00	-.84	.402	
SemanticsHighly: Nonword Repetition	.00	.02	2367.00	-.09	.930	
SessionT2:SemanticsHighly:NWR	.01	.03	2367.00	.53	.598	

Random effects	Variance	SD
Participant: (intercept)	.03	.18
Target: (intercept)	.01	.08

* p<.05, ** p<.005, *** p<.001

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