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Eye-tracking the time-course of novel word learning and lexical competition in adults and children ☆

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ABSTRACT

Lexical competition is a hallmark of proficient, automatic word recognition. Previous research suggests that there is a delay before a new spoken word becomes engaged in this process, with sleep playing an important role. However, data from one method – the visual world paradigm – consistently show competition without a delay. We trained 42 adults and 40 children (aged 7–8) on novel word-object pairings, and employed this paradigm to measure the time-course of lexical competition. Fixations to novel objects upon hearing existing words (e.g., looks to the novel object *biscal* upon hearing "*click on the biscuit*") were compared to fixations on untrained objects. Novel word-object pairings learned immediately before testing *and* those learned the previous day exhibited significant competition effects, with stronger competition for the previous day pairings for children but not adults. Crucially, this competition effect was significantly smaller for novel than existing competitors (e.g., looks to *candy* upon hearing "*click on the candle*"), suggesting that novel items may not compete for recognition like fully-fledged lexical items, even after 24 h. Explicit memory (cued recall) was superior for words learned the day before testing, particularly for children; this effect (but not the lexical competition effects) correlated with sleep-spindle density. Together, the results suggest that different aspects of new word learning follow different time courses: visual world competition effects can emerge swiftly, but are qualitatively different from those observed with established words, and are less reliant upon sleep. Furthermore, the findings fit with the view that word learning earlier in development is boosted by sleep to a greater degree.

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1. Introduction

The relative ease with which we can learn new words, after very few exposures is well documented in both the developmental (Bloom & Markson, 1998; Carey & Bartlett, 1978; Speigel & Halberda, 2011) and adult literature (e.g., Dahan, Magnuson, Tanenhaus, & Hogan, 2001; Luce & Pisoni, 1998; Marslen-Wilson & Warren, 1994). However, word learning is a multi-faceted process. When a new spoken word is learned we must not only recognise its phonological form but also develop a detailed semantic representation of its meaning and integrate both form and meaning with existing semantic and lexical networks. The phonological form may be learned swiftly. However, developing a fully-fledged representation requires repeated exposures over time with the representation developing in richness with each encounter. When we perceive a sequence of speech, a lexical competition process takes place in order to identify the familiar words that most closely match the sequence (Gaskell & Marslen-Wilson, 2002; Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris, 1994). Thus, a discerning measure of whether a newly acquired word has been integrated in the mental lexicon is its engagement in this automatic lexical competition process, which can only arise once it has been fully integrated with existing forms in the lexicon. McMurray, Kapnoula, and Gaskell (in press) provide a comprehensive discussion of the way in which lexical items can be conceptualised as pathways comprising dynamic and multi-faceted mappings between phonological, semantic and orthographic representations. On this view, competition between lexical items may well arise as a result of the increasing automaticity of activation of these pathways, leading to flexible and efficient word recognition. Previous research with adults has suggested that a consolidation period, often associated with sleep, is required before novel spoken words can be accessed

☆ Please note that the data presented in this manuscript, including the code used to produce the eyetracking analyses, are publicly available at https://osf.io/wvy27.

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automatically and compete for recognition with existing words (Dumay & Gaskell, 2007; Lindsay & Gaskell, 2013; Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010). These findings are well-explained by a *complementary systems* account of word learning in which novel words are initially learned via hippocampal mediation between the relevant neocortical regions. Sleep then provides an opportunity for hippocampal replay to support integration of the new mappings with existing knowledge in neocortical long-term memory (Davis & Gaskell, 2009; McClelland, McNaughton, & O'Reilly, 1995). A remarkably similar emergence of lexical competition after sleep has been reported in children (Henderson, Weighall, Brown, & Gaskell, 2012), suggesting that the same framework can account for word learning in development.

However, recent reports of competition effects immediately after learning have sparked debate over the extent to which offline consolidation is *necessary* for lexical competition effects to emerge (e.g., Coutanche & Thompson-Schill, 2014; Fernandes, Kolinsky, & Ventura, 2009; Kapnoula & McMurray, 2016; Kapnoula, Packard, Gupta, & McMurray, 2015). Such immediate effects seem to emerge under certain conditions or with particular methodologies, including when training involves extensive exposure (Fernandes et al., 2009) or promotes 'co-activation' of novel and familiar words (Coutanche & Thompson-Schill, 2014; Kapnoula et al., 2015; Lindsay & Gaskell, 2013). Thus, whilst offline consolidation plays a crucial role in lexical integration and in improving automaticity (Geukes, Gaskell, & Zwitserlood, 2015; Tham, Lindsay, & Gaskell, 2015), the emergence of lexical competition likely follows a graded trajectory dependent upon factors both intrinsic and extrinsic to the learner (McMurray et al., in press, for a review).

The present study employed the visual world paradigm, which has revealed immediate competition effects in previous studies (e.g., Creel, Aslin, & Tanenhaus, 2008; Kapnoula & McMurray, 2016; Kapnoula et al., 2015; Magnuson, Tanenhaus, Aslin, & Dahan, 2003). We compared performance for items learned just before testing with those learned on the previous day. Importantly, we also sought to determine whether the magnitude of any observed competition effects would be comparable to those observed for existing lexical items, and therefore whether immediate engagement in competition is indicative of rapid neocortical learning. Finally, we compared the performance of adults to that of children aged 7- to 8- years old to examine whether the adult-like pattern of performance found in previous studies is evident when a more temporally sensitive measure of lexical competition is utilised.

A substantial number of studies provide evidence for a protracted time-course of engagement in lexical competition in adults (e.g., Bakker, Takashima, van Hell, Janzen, & McQueen, 2014; Dumay & Gaskell, 2007; Gaskell & Dumay, 2003; Tamminen et al., 2010). Many of these studies used the pause detection paradigm as a measure of lexical competition (Mattys & Clark, 2002). Participants were exposed to fictitious spoken novel competitors (e.g., *dolpheg*) that overlapped with existing words (e.g., *dolphin*) and made speeded judgements on the presence/absence of a 200 ms pause inserted near the point in the word at which it deviated from the new competitor (e.g., "*dolph_in*"). Soon after learning there was no difference in pause detection latencies for the existing words compared with matched control words for which no close competitor had been learned; however, after a delay (particularly when the delay involved sleep; Dumay & Gaskell, 2007), a lexical competition effect emerged (i.e., the existing words were responded to more slowly than the control words). A similar sleep-associated improvement was found for recall and recognition of the novel items, consistent with the view that sleep works to *strengthen* as well as *integrate* new lexical knowledge (Rasch & Born, 2013; Schreiner & Rasch, 2016).

Children learn thousands of words with ease; hence one might predict a less protracted time course of word learning earlier in development. Nevertheless, sleep-associated lexical competition effects have also been revealed in children, suggesting that sleep facilitates lexical integration in the developing brain (Henderson et al., 2012) in a similar manner. The same pattern of delayed lexical competition is observed when children learn real rather than fictitious words (e.g., *hippocampus* competing with *hippopotamus*), when word meanings and picture referents are provided (Henderson, Weighall, Brown, & Gaskell, 2013) and when novel words are learned more implicitly via stories (Henderson, Devine, Weighall, & Gaskell, 2015). More recently, Horváth, Myers, Foster, and Plunkett (2015) taught two novel object-word pairs to 16 month-old infants, testing lexical knowledge via a preferential looking task, both prior to and following a nap or equivalent period of wake. Whilst the nap group improved after the nap, the wake group did not change.

These findings, from across development, are consistent with a *complementary learning systems* account of vocabulary acquisition (Davis & Gaskell, 2009; McClelland, McNaughton, & O'Reilly, 1995), as well as *active systems* models of sleep-dependent consolidation (Born & Wilhelm, 2012; Diekelmann & Born, 2010; Rasch & Born, 2013). According to the complementary systems account, acquiring new words too quickly can disrupt memory for similar items already in long-term memory. Hence, in order to protect existing items from "catastrophic interference", new words are encoded using short-term hippocampal mediation, before a long-term neocortical memory representation is strengthened via consolidation (see Davis, Di Betta, Macdonald, & Gaskell, 2009, for fMRI evidence in support of this theory). Consistent with this, the active systems model posits that slow oscillations in sleep drive the transfer of initially hippocampally mediated memory traces to neocortical sites for long-term storage. Slow oscillations comprise up-states with wake-like levels of firing activity, and down-states of neuronal silence. The up-states of slow oscillations are temporally synchronized with two key EEG events – thalamocortical spindles and sharp-wave ripples – which are proposed to signal recently learned memory reactivations from the hippocampus and facilitate integration into neocortical storage sites (e.g., Mölle, Bergmann, Marshall, & Born, 2011). For example, Tamminen et al. (2010) reported positive correlations between overnight increases in lexical competition and sleep spindles in adults, and between slow-wave sleep (SWS) duration and increases in recognition speed to newly learned words. Not only does this support an active role of sleep in the consolidation of newly acquired words, it also hints at a multiplicity of method underlying different aspects of word learning.

Children sleep more than adults, display more SWS, and show increased levels of slow oscillation activity, peaking at 10–12 years (Kurth et al., 2010; Ohayon, Carskadon, Guilleminault, & Vitiello, 2004). In this light, it is not surprising that children have been reported to show enhanced sleep-dependent consolidation for explicit aspects of declarative memory than compared to adults (Wilhelm et al., 2013). Despite the remarkably similar time-course of lexical competition for novel words in children (e.g., Henderson et al., 2012; although cf. Brown, Weighall, Henderson, & Gaskell, 2012), there have been important differences in the magnitude of the competition effects, with children showing larger effects than adults even when baseline RT is controlled (Henderson, Weighall, Brown, et al. et al., 2013). Furthermore, Henderson et al. (2015) reported larger overnight increases in lexical competition for children relative to adults, although such an effect appeared to be due to baseline differences in response speed which was slower in the children. Thus the states under which we see enhanced sleep-dependent consolidation in childhood, remains to be determined.

The visual world paradigm (VWP) is also sensitive to lexical competition effects in adults and children, with eye movements

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