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Review article

Consolidation of vocabulary during sleep: The rich get richer?

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A B S T R A C T

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

Contents

1. Introduction

Building a good vocabulary is a crucial task for the developing child, enabling successful communication with others in both spoken and written language. A poor vocabulary places constraints

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

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

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

2. Systems consolidation and the role of sleep

It is well accepted that memory is not a unitary store in which all information is stored and accessed in the way it was initially encoded (McGaugh, 2000). Although the hippocampus and other regions of the medial temporal lobes are known to play crucial roles in memory, studies of patients with hippocampal damage demonstrated that individuals could retain some memory of earlier life experiences (e.g., Scoville and Milner, 1957). From this, it has been concluded that memories may become gradually independent of the hippocampal system over time (Squire and Alvarez, 1995; Squire and Zola-Morgan, 1991) via a process coined *systems consolidation*. Although the nature of the different memory systems and the mechanisms that enable their interaction remain hotly debated in memory research (e.g., Nadel et al., 2007), there is good evidence to suggest that memory reorganisation continues for the months and even years after first encountering new information (e.g., Takashima et al., 2006).

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

2.1. Slow-wave sleep (SWS) and memory

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

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