Brain and Language; Volume 167, April 2017, Pages 1-2

https://doi.org/10.1016/j.bandl.2017.02.002

Sleep and Language Learning

Introduction

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Language learning is a fundamental to enable communication between humans. Only with advanced skills in a native language, an individual will be able to share and understand thoughts and feelings with others on a complex level, allowing a proper integration of the individual in a society. In addition, learning not only one's own native language, but also other languages represents a key challenge for multilingual societies, providing the fundamental basis for understanding, constructive discussion and tolerance in our international world.

While it is obvious that key factors of learning a native or foreign language are active training, repeated exposure and practice, additional mechanisms facilitate the acquisition and storing of language skills during this process. For example, learning and long-term storage of any information requires a period of stabilization and integration of this newly acquired knowledge into long-term memory networks of the brain (Dudai, 2004; Squire & Wixted, 2011). This process is termed consolidation, which includes both local stabilization of information on the synaptic level (synaptic consolidation) as well as integration and abstraction of information between different memory systems in the brain (systems consolidation). It is assumed that the consolidation of memories after learning consists of several waves of consolidation, lasting from seconds to minutes over hours and days up to months and years (McGaugh, 2000). For language learning, several complex aspects need to be consolidated and integrated into long-term memory: For example, language learning does not only include the acquisition of the meaning of concrete words, but also the pronunciation of these words, the particular speech sounds of a language, the grammatical rules of the language and many other aspects. All this information then needs to be integrated in a proper network allowing almost effortless access and use of this information in skilled language learners for the long-term.

What are the mechanisms of this sophisticated and complex consolidation process of newly acquired language skills? It has been proposed that off-line periods like sleep facilitate the consolidation of memories (Rasch & Born, 2013). During sleep, the conscious processing of external and internal information is attenuated, reducing the ability of acquiring new information. Thus, sleep provides an ideal window of opportunity to reprocess, stabilize and integrate already acquired information into long-term memory networks. In addition to such a passive role of sleep for memory consolidation, it is now widely accepted that sleep also plays an active role in the consolidation of memories. For example, it has been shown that newly acquired memories are spontaneously and repeatedly

reactivated during specific stages of sleep, particularly during Non-rapid eye movement sleep (NonREM sleep) and/or slow-wave sleep (SWS) as opposed to REM sleep (O'Neill, Pleydell-Bouverie, Dupret, & Csicsvari, 2010). During this reactivation, newly learned information is repeatedly replayed in the sleeping brain, providing a possible neuronal mechanism for the stabilization of memories, but also for the integration and abstraction of this information into long-term memory. This reactivation process during sleep might be particularly relevant for the long-term acquisition of language skills, providing the basis for a stabilization and integration of newly acquired words and semantic concepts of a language, but also for shaping the neural representation of language prosody, grammatical rules and more. Thus, consolidation of memories during sleep might be a key to reach advanced levels in multiple language skills.

Unfortunately, in the research field of language learning, the concept and importance of memory consolidation have only begun to be thoroughly explored, and the exact role of sleep in language learning is still poorly understood. On theoretical grounds, Gaskell and colleagues have proposed the complementary learning systems (CLS) account to incorporate consolidation and sleep in theories of languag learning (Davis & Gaskell, 2009, see also Weighall et al., this issue). To further stimulate research in this direction, this special issue on "Sleep and Language Learning" is intended to bring together some of the recent findings in this rapidly growing field. My hope would be that consolidation and sleep become basic concepts of high relevance in the field of language learning in the near future.

The special issue of "Sleep and Language Learning" consists of eight original research articles and two reviews. In the first article, **Simon and colleagues** initiate the topic by reporting a beneficial role of sleep on language learning in 6.5-month-old infants. In their study, infants listened to an artificial language and then were either allowed to nap or stayed awake. Afterwards, memory was tested using the well-established head-turn preference procedure. Interestingly, infants who napped after learning showed signs of retention for the newly learned words, whereas infants in the wake group did not. Thus, memory consolidation during sleep facilitates language learning already at very early stages in infants. Similarly, in the second paper, **Weighall and colleagues** used eye-tracking in children and adults to examine the time-course of novel word learning. Their results generally confirm a beneficial role of a 24-hour consolidation period including sleep for explicit memory of novel words. Interestingly, children profited more from this consolidation period as compared to adults, particularly with respect to lexical integration of these words. The results again suggest that benefits of off-line consolidation periods on language learning are particularly relevant during early developmental periods.

The third study focusses on the influence of reward on the consolidation of newly learned word-pairs. **Studte et al.** tested the associative memory performance of young adults before and after a 90 min nap. As expected, highly rewarded word-pairs were generally better recognized as word-pairs associated with low reward. In addition, memory for highly rewarded word-pairs correlated positively and selectively with the density of sleep spindles during the nap. These findings support the general assumption that relevant information is preferentially consolidated during sleep. **Monaghan and colleagues** used a different approach in their study. They asked their participants to learn several lists of semantically related words according to the classical Deese-Roediger-McDermott (DRM) paradigm examining true and false memories (Roediger & McDermott, 1995). Consistent with a role of sleep in processes of abstraction, the authors replicated previous findings of a higher false memory rate after sleep as compared to waking (Diekelmann, Born, & Wagner, 2010).

Furthermore, the authors observed that sleep shifted memory advantages to words presented in the right visual field. These exciting results suggest that sleep might play a role in redistributing verbal memories to the left hemisphere associated with most efficient language processing, although more research is needed here to clarify this proposition.

The fifth and sixth study of the special issue used functional brain imaging to examine the formation and consolidation of novel language aspects. **Takashima and colleagues** examined the change of neural correlates of novel word acquisition across? a period of one? week. They report that lexical integration was present not immediately, but after a consolidation period of one week , and it was accompanied by a stronger neocortical activation and inter-cortical functional connectivity. Again, these findings support the notion that memory consolidation plays a fundamental role on the successful integration of newly acquired words. Along similar lines, **Sterpenich and colleagues** showed that sleep (as compared to sleep deprivation) after learning improved memory for newly learned nonwords and led to a better performance in a lexical decision task for these nonwords. In addition, hippocampal activation was increased for these words only in the sleep group, both for the lexical decision task and the memory retrieval task. These findings suggest that sleep fosters consolidation processes necessary for acquisition and integration of novel words, rendering these words more easily accessible during later retrieval processes.

The seventh and eighth study tackle the exciting question whether reprocessing of verbal information can be accessed and influenced during off-line states like sleep. For example, **Blume and colleagues** exposed participants to non-awakening verbal information during sleep while brain oscillations were recorded using electroencephalography (EEG). By means of event-related potentials, they show that preferential processing of emotional and self-relevant information persists even during NonREM, during which the level of consciousness of the participants is reduced to a minimum. Thus, processing of external verbal information during sleep is largely maintained during NonREM sleep. **Baterrink and colleagues** made use of this ability, and tested whether the processes of memory reactivation and consolidation occurring spontaneously during sleep can be further improved by presented verbal information during sleep, using a method called targeted memory reactivation (TMR). In particular, they focused on the learning and generalization of new grammatical rules. They showed that participants who were again exposed to the artificial language during sleep had larger gains in grammatical generalization as compared to participants who slept without TMR. This exciting possibility of enhancing language processing by re-exposure to language cues during sleep is then summarized and reviewed in the overview of **Schreiner and colleagues.** The authors outline different lines of evidence and theoretical accounts arguing in favor of a spontaneous reactivation and consolidation of memories during sleep. In addition, the authors summarize studies of improving memory consolidation by TMR during sleep, in particular in the field of vocabulary learning. Thus, re-exposure to newly learned foreign vocabulary during sleep significantly and consistently improves memory for the translations of these new words. During sleep, the successful reactivation of the newly acquired vocabulary is accompanied by a characteristic oscillatory signature, involving oscillations both in the spindle and theta range. These results strongly suggest that (a) reactivation of language aspects during sleep is an important mechanism underlying successful language learning which (b) can be further improved by re-exposure to non-awakening language cues during sleep. While the benefit of TMR during sleep has been now shown for vocabulary learning and generalization of grammatical rules, future studies will need to examine whether further aspects of language learning (novel word acquisition, acquisition of foreign speech sounds, lexical integration etc.) also profit from re-exposure to language cues during sleep.

Last but not least, **Kurdziel and colleagues** provide an excellent overview of a possible role of sleep in novel word learning in aging. They argue that sleep quality and quantity of sleep strongly decrease with age. Simultaneously, aging is typically accompanied by a decreased ability of learning novel words. Thus, they state and present first studies showing that there might be an inter-relation between aging, sleep and language learning. The authors hypothesize that sleep-dependent consolidation of newly learned worlds as well as lexical integration of these words might be more strongly impaired in older adults as compared to younger adults due to reductions in sleep quality and quantity, although future studies need to confirm this hypothesis.

In sum, the results and overviews convincingly argue in favor of processes of memory consolidation and sleep as important concepts in language learning. Future studies are needed to examine the mechanisms and boundary conditions of consolidation processes for language learning. In addition, studies outside of the laboratory are required to investigate and stimulate the usefulness of sleep after language learning in educational settings. Furthermore, targeted memory reactivation during sleep might be an exciting method to enhance different aspects of language learning over the life span.

Acknowledgements

This work was supported by a grant from the Swiss National Science Foundation (SNSF) (100014_162388). I want to thank Maren Cordi for helpful comments on earlier versions of the manuscript.

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