Neuropsychologia ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Sleep facilitates learning a new linguistic rule

Laura J. Batterink*, Delphine Oudiette, Paul J. Reber, Ken A. Paller

Northwestern University, Department of Psychology, 2029 Sheridan Road, Evanston, IL 60208, United States

ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form
16 September 2014
Accepted 19 October 2014

Keywords:
Language acquisition
Implicit learning
Slow-wave sleep
REM
Event-related potentials

ABSTRACT

Natural languages contain countless regularities. Extraction of these patterns is an essential component of language acquisition. Here we examined the hypothesis that memory processing during sleep contributes to this learning. We exposed participants to a hidden linguistic rule by presenting a large number of two-word phrases, each including a noun preceded by one of four novel words that functioned as an article (e.g., *gi rhino*). These novel words (*ul*, *gi*, *ro* and *ne*) were presented as obeying an explicit rule: two words signified that the noun referent was relatively near, and two that it was relatively far. Undisclosed to participants was the fact that the novel articles also predicted noun animacy, with two of the articles preceding animate referents and the other two preceding inanimate referents. Rule acquisition was tested implicitly using a task in which participants responded to each phrase according to whether the noun was animate or inanimate. Learning of the hidden rule was evident in slower responses to phrases that violated the rule. Responses were delayed regardless of whether rule-knowledge was consciously accessible. Brain potentials provided additional confirmation of implicit and explicit rule-knowledge. An afternoon nap was interposed between two 20-min learning sessions. Participants who obtained greater amounts of both slow-wave and rapid-eye-movement sleep showed increased sensitivity to the hidden linguistic rule in the second session. We conclude that during sleep, reactivation of linguistic information linked with the rule was instrumental for stabilizing learning. The combination of slow-wave and rapid-eye-movement sleep may synergistically facilitate the abstraction of complex patterns in linguistic input.

1. Introduction

The extraction of patterns from linguistic input lies at the core of language learning. Natural languages are governed by complex regularities at virtually every level. For example, within a given language, certain sound combinations commonly co-occur while others are illegal (e.g., *pl* versus *tl* onsets in English). Words can be combined into phrases and sentences only in limited ways, specified by syntactic rules (e.g., articles such as *the* or *my* are not followed by verbs). Subtle regularities can even predict the lexical category of a word (Farmer et al., 2006). Most native speakers have little insight into these regularities, even though this knowledge is essential for comprehension and production (Paradis, 2004). Acquisition of these regularities typically occurs implicitly in children, in the absence of intention to learn or awareness of what has been learned (Paradis, 2004; Ullman, 2004). Pattern extraction for learning linguistic regularities certainly occurs online during training, but here we consider whether offline processes during sleep may also play a role.

The general importance of sleep for memory consolidation, as well as for the extraction of rules, has been repeatedly demonstrated (Stickgold and Walker, 2013). For example, sleep can lead to insight in a rote mathematical task (Wagner et al., 2004), gains in transitive inference (Ellenbogen et al., 2007), improvements in statistical sequence learning (Durrant et al., 2011, 2013), and enhanced category learning (Djonlagic et al., 2009). Memories that share common elements may be reactivated during sleep in a way that promotes shared connections (Lewis and Durrant, 2011). If idiosyncratic aspects of each memory are also lost over time, a general schema may result. In the context of language acquisition, this schema could represent overarching linguistic rules abstracted over multiple exemplars and learning episodes (e.g., knowledge that the *-s* morpheme indicates plurality).

Our aim was to test whether sleep mechanisms promote rule generalization in a language-learning context. We built upon a paradigm developed by Leung and Williams (2012, 2014), in which participants were presented with phrases containing four novel articles (*gi*, *ul*, *ro* and *ne*). Participants were explicitly instructed that these novel articles encode distance, with two of the articles used

* Corresponding author.
E-mail address: lbatterink@northwestern.edu (L.J. Batterink).

http://dx.doi.org/10.1016/j.neuropsychologia.2014.10.024
0028-3932/

when the accompanying noun refers to a nearby object, and the other two used when the accompanying noun refers to objects that are far away. However, unbeknownst to participants, the use of these articles was also governed by a second semantic feature involving noun animacy: two of the articles (*gi* and *ul*) were used for animate nouns and the other two (*ro* and *ne*) for inanimate nouns. Participants responded to each phrase by indicating whether it contained an animate or inanimate object, such that processing of noun animacy was assured. A final violation block, consisting of phrases in which the mapping between articles and animacy values was reversed, was presented at the end of the experiment. Using this paradigm, Leung and Williams found that participants' responses to trials in the violation block were delayed, even when they reported no awareness of this regularity. This finding provides evidence that adults can implicitly learn mappings between grammatical form and meaning. This ability is a key component of language acquisition, as associations between form and meaning underlie virtually all aspects of language.

In the present study, as in Leung and Williams, participants responded to phrases composed of a novel article and noun (e.g., *ul spider*) that either conformed to or violated a hidden linguistic animacy rule. However, we adapted Leung and Williams' original paradigm by presenting violation trials interspersed throughout the learning block, rather than in a separate block at the end of learning, in order to track the time course of learning effects (Fig. 1). We also recorded event-related brain potentials (ERPs) to provide additional measures of learning and rule awareness. We hypothesized that learning of the hidden rule should be evident in slower responses to phrases that violated the rule, similar to previous findings (Leung and Williams, 2012, 2014). We additionally hypothesized that ERP differences would emerge between canonical and violation phrases as participants implicitly learned the hidden rule, representing a neural index of learning. In addition, we hypothesized that participants who became aware of the rule would show a P600 effect to violation phrases, a positive-going deflection with a typical latency between 600 and 1000 ms (Friederici, 2002). This component has been previously linked to the conscious detection of a syntactic violation (Batterink and Neville, 2013). In contrast, participants who remained unaware of the rule should not show this effect. To examine whether sleep influences the implicit learning of associations between form and meaning, participants were exposed to phrases containing the four novel articles, subsequently napped, and were then tested on new phrases upon awakening.

The critical experimental question was whether measures of learning changed as a function of sleep mechanisms. We examined SWS and REM (slow-wave sleep and REM sleep), as well as their interactions, guided by theories about the roles of these sleep stages (Diekelmann and Born, 2010; Walker and Stickgold, 2010; Stickgold et al., 2000). We adopted a correlational approach, which previously implicated a synergism between SWS and REM sleep (e.g., Stickgold et al., 2000; Cairney et al., 2014). This approach avoids a shortcoming of conventional sleep/wake comparisons, wherein improvements in behavioral performance can be attributed either to memory enhancement over a retention interval with sleep compared to one without sleep, or to memory reduction secondary to interference (i.e., greater interference during waking than during sleep) and/or arousal effects (i.e., higher alertness after sleep than an equivalent period of wake). We thus focused on the degree to which the learning changed after sleep, in order to determine whether sleep processing contributes to the abstraction of linguistic rules. In particular, we predicted that duration of SWS, REM, and/or interactions between SWS and REM would correlate with an increase in implicit knowledge of the hidden rule, as reflected by larger reaction time (RT) differences to violation versus canonical phrases after sleep.

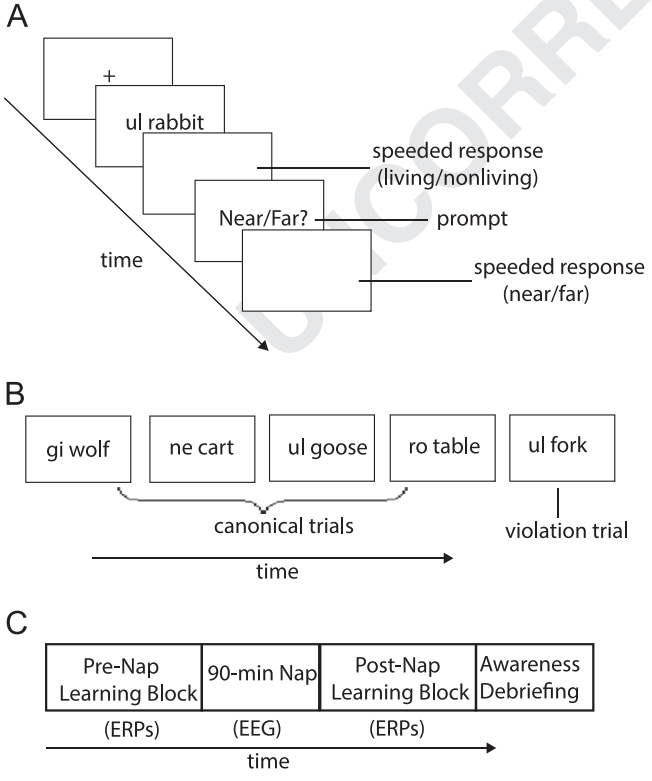

Fig. 1. Summary of experimental task and overall paradigm. A) Sequence of events in a typical trial. B) Representation of the trial structure in the experimental task. One out of every seven trials was a violation trial (~14%). Violation trials were interspersed unpredictably throughout the experimental task. C) Each learning block was comprised of 308 unique trials. A 90-min nap separated the two learning blocks.

2. Materials and methods

2.1. Participants

Twenty-nine right-handed, neurologically normal native English speakers (17 female; age range, 18.3–25.4 years) participated in this study.

2.2. Experimental task

Building on the methodology used by Leung and Williams (2012, 2014), as described above, participants were trained on an artificial article system composed of four novel articles: *gi, ro, ul,* and *ne*. They were instructed that these articles functioned like the English word "the" but that they also designated relative distance, with two of them (*gi* and *ro*) meaning "near" and the other two (*ul* and *ne*) meaning "far." However, participants were *not* told that the four novel articles also predicted the animacy of the subsequent noun (Table 1). Before beginning the main experimental task, participants were pre-trained for approximately 15 min on the

Table 1
Miniature article system[a].

	Participants were *not* told…	
	Animate	Inanimate
Participants were told…		
Near	gi	ro
Far	ul	ne

[a] Leung and Williams (2005) showed that the precise assignment of articles to animacy values (i.e., whether ul and gi are assigned to animate nouns and ne and ro to inanimate nouns, or vice versa) had no significant effect on learning. Therefore, in the present study, animacy assignment for the four articles was kept consistent across participants.

Please cite this article as: Batterink, L.J., et al., Sleep facilitates learning a new linguistic rule. Neuropsychologia (2014), http://dx.doi.org/10.1016/j.neuropsychologia.2014.10.024