Electrophysiological and haemodynamic biomarkers of rapid acquisition of novel wordforms

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SUMMARY

Humans are unique in developing large lexicons; to achieve this, they are able to learn new words rapidly. However, neural bases of this rapid learning, which may be an expression of a more general mechanism rooted in plasticity at cellular and synaptic levels, are not yet understood. Here, we highlight a selection of recent EEG and fMRI studies that attempted to trace word-learning in the human brain non-invasively. They show a rapid development of cortical memory traces for novel wordforms over a short session of auditory exposure to these items. Moreover, they demonstrate that this effect appears to be independent of attention, reflecting a largely automatic nature of word acquisition. At the same time, it seems to be limited to stimuli with native phonology, likely benefiting from pre-existing perception-articulation links in the brain, which suggests different neural strategies for learning words in native and non-native languages. We also show a complex interplay between overnight consolidation, amount of exposure to novel vocabulary and attention on speech input, which all influence learning outcomes. In sum, the available evidence suggests that our brain may effectively form new cortical circuits online, as it gets exposed to novel linguistic patterns in the sensory input. A number of brain areas, most notably in hippocampus and neocortex, appear to take part in word acquisition. Critically, the currently available data not only demonstrate hippocampal role in rapid encoding followed by slow-rate consolidation of cortical memory traces, but also suggest immediate neocortical involvement in the word memory trace formation.

Keywords: brain, cortex, word learning, fast mapping

INTRODUCTION

Humans are unique in developing large lexicons as their communication tool; to achieve this, they are able to learn new words rapidly. However, neural bases of this rapid learning, which may be an expression of a more general cognitive mechanism likely rooted in plasticity at cellular and synaptic levels, are not yet understood. In this presentation, we highlight a selection of recent studies that attempted to trace word-learning in the human brain non-invasively (e.g., Breitenstein et al., 2005; De Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Lévi, 2007; Mestres-Misse, Rodriguez-Fornells, & Munte, 2007). To explore this in more detail, we will present our own EEG and fMRI studies that demonstrate rapid development of cortical memory traces for novel word forms over a short session of passive auditory exposure to these items.

EEG EVIDENCE OF RAPID WORD LEARNING

In the first EEG studies (Shtyrov, 2011; Shtyrov, Nikulin, & Pulvermüller, 2010), we exposed our subjects to familiar words and novel spoken stimuli in a short passive perceptual learning session in which the subjects were not instructed to pay attention to the stimuli or actively memorize them. We compared automatic ERP brain responses to these items throughout the learning exposure. Initially, we found enhanced early (~100 ms) electrophysiological activity for known words, indexing the ignition of their underlying memory traces. However, just after 14-20 minutes of learning exposure, the novel items exhibited a significant increase in response magnitude matching in size with that to real words. This activation increase reflects rapid mapping of new word forms onto the lexicon. Similar to familiar words, the neural activity subserving rapid learning of new word forms was generated in the left-perisylvian language cortex, especially anterior superior-temporal areas, as suggested by distributed source analysis of the ERP data. These phenomena were found in independent experiments using both English (Shtyrov et al., 2010) and Finnish (Shtyrov, 2011) subjects and stimuli, and were confirmed using both factorial and linear regression analyses. Furthermore, acoustically matched novel non-speech stimuli did not demonstrate similar response increase, suggesting neural specificity of this rapid learning phenomenon to linguistic stimuli (Shtyrov, 2011).

AUTOMATICITY AND SPEECH SPECIFICITY

To investigate the role of attention and phonological properties in rapid learning phenomena, we ran a further study, in which the subjects were repeatedly presented with (i) known words, (ii) phonotactically legal and phonologically native novel wordforms and (iii) novel pseudowords with non-native phonology. In a counterbalanced design, they were either asked to pay close attention to the stimuli and memorize them, which was tested using a battery of memory tests, or ignore the stimulation and concentrated on a primiary non-linguistic task. We found (Kimppa et al., in prep.) that, in the passive condition, a negative-going ERP peak at ~50 ms after the disambiguation point was strongest for the real words and weakest for the non-native words. Further, while there was a habituation in this early word response, ERPs to both pseudoword types did not show such habituation effects. Crucially, the ERP response to pseudowords with native phonology increased during the short recording session to resemble the initial response magnitude of words, while non-native stimuli did not show such rapid-learning dynamics. Whereas the phonologically native pseudowords and words showed similar dynamics in the attend condition (albeit later, at ~80 ms), non-native stimuli exhibited a decrease in their activation. The results suggest that rapid formation of novel memory traces for phonologically plausible stimuli takes place automatically in both passive and attentionally-demanding condition, whereas the role of attention appears to be in successful categorization of the spoken word-like input. Memory trace formation for words with non-native phonology does not seem to take in the passive exposure, at least with the amount of repetition used in this experiment; furthermore, it appears to be suppressed in the attend condition. The results suggest phonetically restricted, attention-modulated rapid learning and plastic changes in the brain reflected by activation pattern changes for novel words. This implies that rapid mapping phenomena are restricted to spoken stimuli with native phonology, benefiting from pre-existing perception-articulation links in the brain, and suggests different neural strategies for learning new words of the native and non-native languages.

RAPID LEARNING VS. CONSOLIDATION: FMRI EVIDENCE

All of the above findings clearly indicate that many exposures to a novel word during a short time may lead to a fast formation of cortical memory traces. Yet, the mainstream view is that the newly learnt items acquire lexical status only after a period of sleep, during which cortical consolidation processes are believed to occur (Davis, Di Betta, Macdonald, & Gaskell, 2009; Davis & Gaskell, 2009; Dumay & Gaskell, 2007). To investigate the effects of sleep and number of exposures on word acquisition, we ran a further fMRI study using stringent behavioral learning regimes and systematically modulating the level of exposure to new vocabulary. We presented our volunteers with spoken familiar words and novel pseudowords during two behavioral training sessions taking place on two consecutive days (day1, day2). The number of times each item was repeated (20 vs. 150) varied orthogonally to the day-of-training. After the training (on day 2), we used fMRI to measure brain responses to these trained and, as a further control, to previously unheard (untrained) items. We found (Garagnani et al., in prep) that brain responses to words and pseudowords in the left STG were differentially modulated by day/training. While word responses were generally smaller and mostly unaffected by training, we found that untrained, day2-trained, and day1-trained pseudowords exhibited increasingly smaller responses (i.e., gradually becoming more and more like real word ones). This is line with previous results, indicating that sleep leads to consolidation of newly acquired representations. When pulling apart data for 20- and 150-times-repeated pseudowords, however, the effects of sleep appear limited mostly to the latter items, suggesting a critical role for the number of repetitions required to set off word learning and consolidation processes. Nevertheless, training does affect brain responses to novel items, even on the same day; hence sleep may not be necessary for changes to observed cortical responses. We also found that pseudoword and word responses are differentially affected by attention (though this effect was not changed by training or sleep), and that attention on stimuli leads to better subsequent memory for pseudowords.

CONCLUSIONS

Echoing early behavioral studies in ultra-rapid word learning, the current experiments can be taken to suggest that our brain may effectively form new cortical circuits online, as it gets exposed to novel linguistic patterns in the sensory input. Critically, the currently available data not only demonstrate hippocampal role in rapid encoding followed by slow-rate consolidation of cortical word memory traces, but also suggest immediate neocortical involvement in the word memory trace formation (Shtyrov, 2012). Whilst the recent data reviewed here can in principle be accommodated by existing conceptual frameworks of learning (such as the complementary learning systems approach), they do call for an update of these concepts that would have to account for a „cortical shortcut" in linguistic memory trace formation (Figure 1). Investigating neural mechanisms of word learning is both a scientifically fascinating endeavour that can shed light on brain underpinnings of language, neuronal plasticity and memory, and an important research avenue for understanding the nature of learning dysfunctions and language deficits linked to a range of hereditary and acquired conditions.

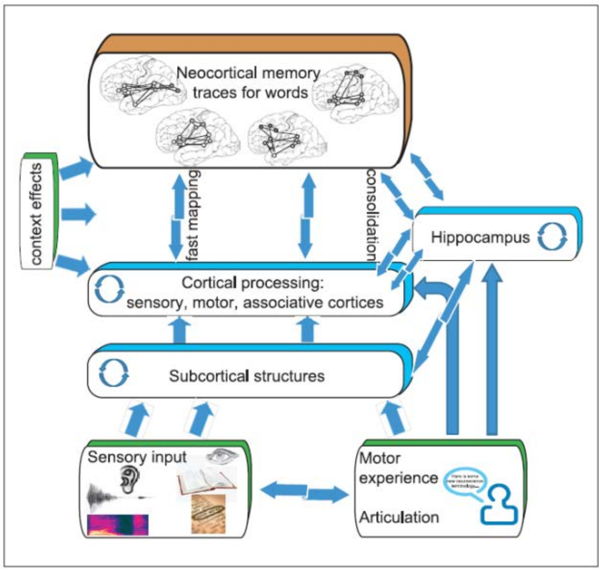

Figure 1. Conceptual sketch of neural bases for word learning (adapted from Shtyrov, 2012). We stress here the putative existence of a fast neocortical route (complementary to the hippocampal route, associated with slower consolidation processes), which may underlie rapid learning and fast mapping phenomena.

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