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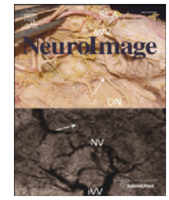

Neural correlates of testing effects in vocabulary learning☆

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ABSTRACT

Tests that require memory retrieval strongly improve long-term retention in comparison to continued studying. For example, once learners know the translation of a word, *restudy* practice, during which they see the word and its translation again, is less effective than *testing* practice, during which they see only the word and retrieve the translation from memory. In the present functional magnetic resonance imaging (fMRI) study, we investigated the neuro-cognitive mechanisms underlying this striking *testing effect*. Twenty-six young adults without prior knowledge of Swahili learned the translation of 100 Swahili words and then further practiced the words in an fMRI scanner by restudying or by testing. Recall of the translations on a final memory test after one week was significantly better and faster for tested words than for restudied words. Brain regions that were more active during testing than during restudying included the left inferior frontal gyrus, ventral striatum, and midbrain areas. Increased activity in the left inferior parietal and left middle temporal areas during testing but not during restudying predicted better recall on the final memory test. Together, results suggest that testing may be more beneficial than restudying due to processes related to targeted semantic elaboration and selective strengthening of associations between retrieval cues and relevant responses, and may involve increased effortful cognitive control and modulations of memory through striatal motivation and reward circuits.

Neural correlates of testing effects in vocabulary learning

Tests that require memory retrieval improve long-term retention more than continued studying (Roediger and Karpicke, 2006b). For example, once learners know the translation of a word, *restudy* practice, during which they see the word and translation again, is less effective than *testing* practice, during which they see only the word and retrieve the translation from memory (Karpicke and Roediger, 2008). This *testing effect* has received much attention from behavioral studies, but its neural correlates are still largely unknown (Roediger and Butler, 2011).

To the best of our knowledge, only two fMRI studies have, so far, explicitly investigated testing effects. Eriksson et al. (2011) scanned participants during a final recall test following prior testing practice, and interpreted correlations between anterior cingulate activation and the amount of prior testing in terms of enhanced memory consolidation. Hashimoto et al. (2011) investigated brain activity related to repeated testing and showed both repetition enhancement and attenuation at the final recall. Both of these studies documented facilitated retrieval processes *after* prior testing. In the present study, we took a different approach and investigated the testing practice phase itself. We directly compared the brain activity related to testing and restudying in order to gain insight into the neuro-cognitive mechanisms by which testing improves memory more than restudying.

Most explanations of testing effects assume that testing improves memory more than restudying because it involves more effortful semantic processing (Roediger and Karpicke, 2006b). More specifically, testing is thought to enhance cognitive effort (e.g., Pyc and Rawson, 2009), which is defined somewhat vaguely as an index of the amount of goal-directed, non-automatic processing (Roediger and Butler, 2011). In this context, testing has also been said to constitute a *desirable difficulty* during learning because it increases beneficial deep semantic processing (Bjork and Bjork, 1992). This could lead to a strengthening of the association between retrieval cues and target information and an improved efficiency of search processes during later recall (e.g., Karpicke and Smith, 2012; Karpicke and Zaromb, 2010), such that irrelevant associations are suppressed and target information comes to mind earlier in response to retrieval cues (Thomas and McDaniel, 2013). Alternatively, testing could improve memory because searching for the correct answer during memory retrievals extends semantic networks around the target information with additional associations, thereby increasing the number of available retrieval cues that can lead to later recall (Carpenter, 2009).

Although these explanations of testing effects are rather abstract, some predictions about possible neural substrates can be derived. First, the inferior frontal gyrus (IFG) has consistently been related to controlled, effortful processing during memory retrieval (Race et al., 2009). More specifically, IFG is thought to maintain retrieval plans

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to favor the activation of relevant information, and to be involved in the selection among competing representations (Badre and Wagner, 2007). Furthermore, IFG activity has been related to semantic processing (Gabrieli et al., 1996; Wagner et al., 1998), during which frontal control processes are thought to act on semantic representations stored in more posterior regions of the brain (Whitney et al., 2011). Although semantic representations are probably distributed across multiple brain areas, a recent meta-analysis of 120 studies suggested that the middle temporal gyrus (MTG) and the inferior parietal lobe (IPL) could function as association areas that integrate different aspects of semantic concepts (Binder et al., 2009). More specifically, MTG and IPL seem to mediate the storage and retrieval of word meaning and the integration of information into larger units for semantic processing (Lau et al., 2008). Therefore, it is likely that the coordinated activity of IFG, MTG, and IPL is involved in testing if effortful, elaborate semantic processing enhances the memory trace.

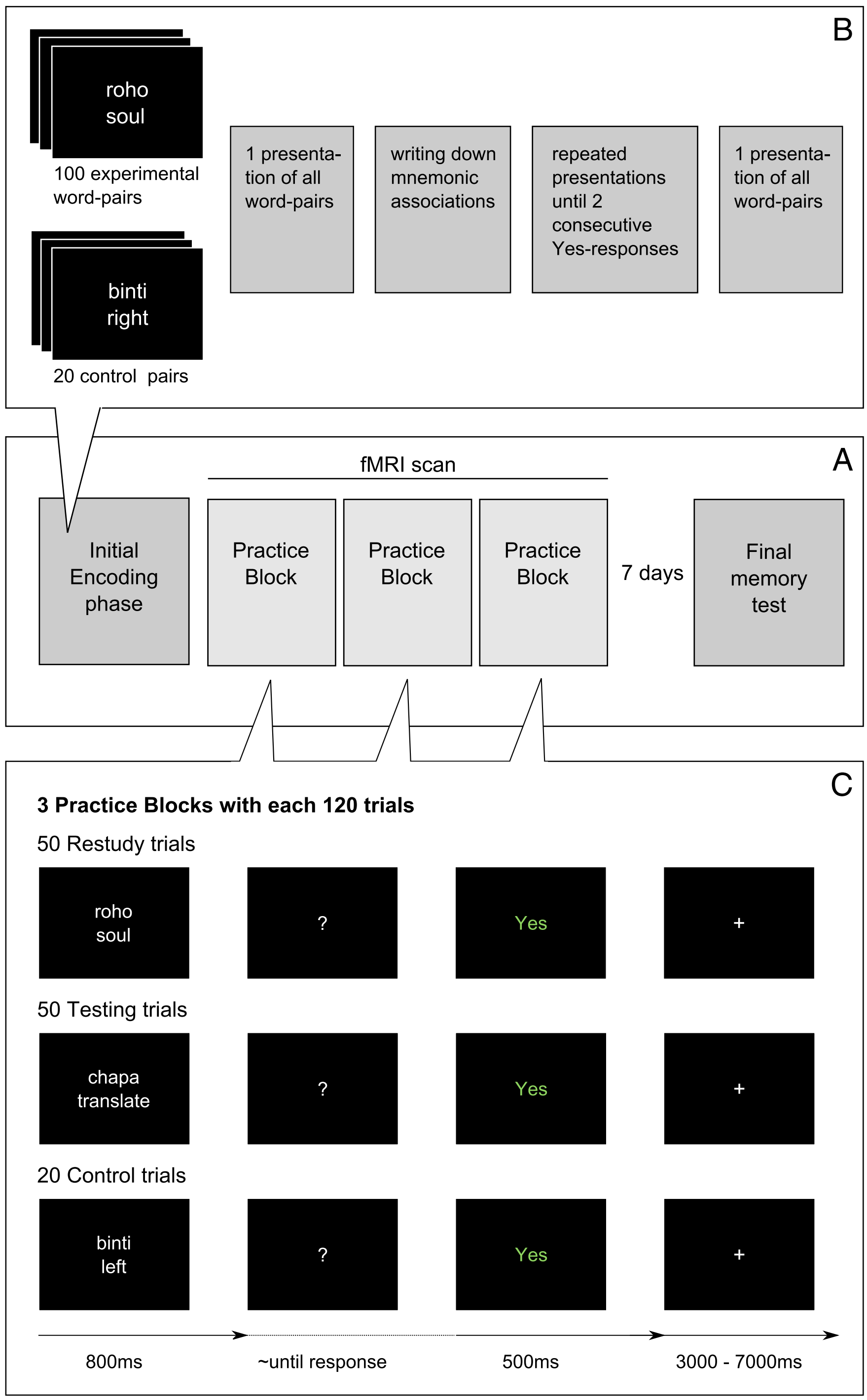

Fig. 1. Experimental procedure. A. Overview of the complete experiment that consisted of an extensive initial encoding phase before scanning, testing and restudy practice in the MR scanner, and a memory test one week later. B. Overview of the four initial encoding tasks with which the participants studied 100 experimental words and 20 control words. C. Overview of the practice trials in the fMRI scanner. This phase contained the critical experimental manipulation: 50 word-pairs were presented in a testing condition with retrieval opportunity, and 50 word-pairs were presented in a restudy condition. In the response phase of both testing and restudy trials, participants pressed a button to indicate whether they thought that they knew the translation of the Swahili word. The response (Yes or No) was displayed for 500 ms. Note that all non-Swahili words were presented in the participants' native language Dutch during the experiment.