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Review article

Neurocognitive mechanisms of the "testing effect": A review

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ABSTRACT

Memory retrieval is an active process that can alter the content and accessibility of stored memories. Of potential relevance for educational practice are findings that memory retrieval fosters better retention than mere studying. This so-called *testing effect* has been demonstrated for different materials and populations, but there is limited consensus on the neurocognitive mechanisms involved. In this review, we relate cognitive accounts of the testing effect to findings from recent brain-imaging studies to identify neurocognitive factors that could explain the testing effect. Results indicate that testing facilitates later performance through several processes, including effects on semantic memory representations, the selective strengthening of relevant associations and inhibition of irrelevant associations, as well as potentiation of subsequent learning.

Contents

1. Memory retrieval as an active process: the testing effect

Memory is typically viewed as a three-step process that begins with the encoding of information, followed by storage and later retrieval of fixed, stable memories. However, this view is incomplete. Retrieval is not a simple read-out process but an *active* process that can change the content and accessibility of memories [1,2]. Of particular interest for educational practice is that prompting retrieval with practice-tests enhances the retention of to-be-learned information over time, as shown in studies on the so-called *testing effect*:"taking a test enhances later performance on the material relative to rereading it or to having no re-exposure at all" [3, p20]. Surprisingly, given the plethora of empirical studies demonstrating the testing effect (see Box 1), there is still limited knowledge of the specific neurocognitive mechanisms involved. In this review, we relate existing cognitive accounts of the testing

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Box 1.

Benefits of memory retrieval: a robust phenomenon

The testing effect is a well-investigated phenomenon in cognitive psychology. For a comprehensive review of behavioral studies, readers are referred to literature overviews in [3,4,49]. Here, we provide a brief introduction to the effect to show that its robustness across different populations, study designs and materials makes it relevant for educational practice.

A typical behavioral testing effect study includes a baseline exposure, followed by either a practice-test or further restudying of the materials, and later a final test to measure learning outcomes (see Fig. 1A). For example, in a study by Roediger and Karpicke [5], students read two prose passages which covered scientific topics, and then restudied one passage and took a practice-test of the other. Learning was assessed five minutes, two days or one week later. Restudying led to better immediate results but practice-testing led to better results on the delayed final tests. This is a common finding in testing effect studies, which often show that the benefits of practice-tests are stronger when the final test is given after a delay rather than immediately after practice (for further information see [43,50–53]).

The testing effect has been replicated across different laboratories and also been documented to reliably improve learning outside the laboratory.

(1) ***The testing effect holds in authentic educational settings using course materials***
Studies have demonstrated the testing effect with course materials [54–60] and real university exams [60], using on-line testing [54], in-class testing [55,56], and classroom response systems ('clickers') [57].

(2) ***The testing effect holds when compared to other pedagogical methods and for different materials***
Testing is more beneficial than pedagogical methods such as mind mapping [12] and group discussions [61], and a better tool for self-study than techniques like reading and highlighting text [62]. The effect was documented with different materials, including materials about geography [63], statistics [60], and medical education [64].

(3) ***The testing effect generates transfer of learning***
Testing enhances the transfer of learning from the specific questions from practice to new problems [63,65–67], enhances re-learning of information [68], and results in higher exam scores [57].

(4) ***The testing effect is beneficial for different populations***
The testing effect has been demonstrated in different age groups, ranging from children [57,58,63] to older adults [69]. Recently, an equally sized testing effect has been demonstrated for individuals suffering from severe traumatic brain injury as compared with healthy individuals [70].

effect to findings from recent brain-imaging studies in order to gain a better understanding of the beneficial effects of memory retrieval on the long-term retention of information. In addition to studies on the testing-effect, available neuroimaging data for the closely related phenomenon of test-potentiated encoding will also be discussed.

2. Cognitive processes underlying the testing effect

Different ideas have been put forward regarding the cognitive processes underlying the testing effect [3–5]. Many of these explanations focus on the way in which testing affects memory representations of the to-be-learned materials. Because most studies on testing effects use verbal materials (e.g., vocabulary or word-pairs), these memory representations are typically conceptualized as (parts of) semantic networks, in which activation spreads among related pieces of information [cf. 6]. Testing is thought to enhance the accessibility of target information by changing the connections within semantic networks, for example, between the representations of two words that are encoded as a word pair [7–10].

Broadly speaking, two different theories exist about the nature of changes in semantic networks. On the one hand, elaboration accounts suggest that semantic networks become richer through testing because additional associations and alternative retrieval routes are formed [7,8]. On the other hand, search-set restriction accounts hold that testing reduces the number of associations that are activated in response to retrieval cues because cue-target associations are selectively strengthened and irrelevant representations are suppressed [9,10].

Carpenter et al. introduced the elaboration account of testing based on the assumption that mental elaboration during the search for the correct answer to a test question extends the semantic network of the tested information by creating or strengthening connections with related concepts [7,8]. These changes in semantic associations are thought to facilitate later recall by providing additional retrieval routes. Support for such accounts comes from studies showing that practice-tests[2] enhance not only memory for presented information, but also for related semantic information that learners generate to associate cue and target information. For example, participants who studied word-pairs like *Mother:Child*, showed better target recall ("*Child*") in response to related semantic mediators like "*Father*" after practice-testing (*Mother:* _____) than after restudying (*Mother:Child*) [11]. In short, representations are thought to get increasingly elaborate with practice-testing so that target information can later be activated through different alternative retrieval routes.

The search-set restriction accounts focus more on the selective nature of retrieval processes during testing, in particular, on the way in which the activation and selection of target information among competing (incorrect) responses influence future retrieval. One theory is that cue-target associations become selectively strengthened such that the memory search hones in on target information while competing associations are suppressed over the course of repeated testing [9,10]. In other words, testing is thought to refine memory representations to selectively strengthen the target response [9,10,12,13]. These ideas have also been linked to the literature on retrieval-induced forgetting. For example, repeatedly retrieving "pineapple" to the cue "fruit- p…..? " facilitates the response "pineapple" but inhibits the alternative response "pear" [14,15]. Selective retrieval, thus, seems to strengthen target responses while inhibiting related but undesired responses.

Recently, Karpicke et al. [16] presented a possible mechanism that could underlie the selection processes during repeated testing. According to their "episodic context account", items become associated with the episodic context in which they are studied. During retrieval, the context from earlier presentations is re-activated and becomes integrated with current contextual

[2] In this article, we use the term "practice-testing" when we describe experimental paradigms, to distinguish testing in the practice phase in which learners engage in retrieval, from the final (performance) test used to measure the outcomes of practice. See also Fig. 1A.