Retrieval-Based Learning: Research at the Interface between Cognitive Science and Education

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Abstract

This essay reviews research on retrieval-based learning, which refers to the general finding that practicing active retrieval enhances long-term, meaningful learning. The idea that retrieval promotes learning has existed for centuries, and the first experiments demonstrating retrieval practice effects were carried out near the beginning of experimental research on learning and memory. Interest in retrieval practice was sporadic during the past century, but the topic has received intense interest in recent years as part of a broader movement to integrate research from cognitive science with educational practice. The essay provides a selective review of foundational research and contemporary work that has been aimed at deepening our theoretical knowledge about retrieval practice and integrating retrieval-based learning within educational activities and settings.

INTRODUCTION

Learning is often identified with the encoding or acquisition of new information. From a learner's perspective, the goal is to get new knowledge and information "in memory," and so the focus of many learners' (and instructors') efforts falls on processes involved in encoding new knowledge. The processes involved in accessing and retrieving that knowledge when it is needed may not be considered much, but even when those processes are considered, retrieval processes are thought of as "neutral" components of learning. If learning happens when new information is encoded, then retrieval can be considered merely an assessment of whether learning happened at all and what was learned. Retrieval may be important because it lets us know what was learned, but retrieval processes themselves are not typically thought to produce learning.

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The research we review in this essay challenges this fundamental idea about the role of retrieval in learning. Research at the intersection of cognitive science and education has shown that retrieval does enhance learning in significant ways. Each act of retrieval changes one's knowledge, improving the ability to retrieve knowledge again in the future. We use the term *retrieval-based learning* to refer both to the fact that retrieval processes contribute greatly to learning and also to activities and instructional approaches that encourage learners to practice retrieval. Engaging in retrieval is a powerful way to promote learning, and understanding retrieval processes is essential for understanding the nature of learning and how to promote it.

Although the idea that retrieval enhances learning may be counter to our everyday intuitions, research demonstrating the effects of retrieval has existed for a century (e.g., Abbott, 1909). Long before the first experiments on the effects of retrieval on learning, philosophers had noted or speculated about the benefits of retrieval practice (e.g., Bacon, 1620/2000). Research on retrieval practice or testing effects enjoyed attention in the beginning of the last century (e.g., Gates, 1917; Jones, 1923–1924; Spitzer, 1939), and there was a short-lived revival of interest in the topic in the early 1970s (e.g., Hogan & Kintsch, 1971, among others), but this interest in retrieval practice was not sustained. In a paper in 1989, John Glover called the effects of retrieval or testing "not gone but nearly forgotten." However, about a decade ago, interest on retrieval practice effects was renewed again (e.g., Roediger & Karpicke, 2006a, 2006b), and retrieval practice continues to receive intense interest in contemporary research.

What has taken retrieval practice from "not gone but nearly forgotten" to an emerging trend and a cutting-edge topic? The renewed interest in retrieval practice has coincided with an unprecedented interest in integrating cognitive science and education. Retrieval-based learning is a prime example of how findings from basic cognitive science can inform educational practice (see Karpicke & Grimaldi, 2012; Roediger, 2013). At the same time, retrieval practice also illustrates how real-world challenges in classrooms must inform research conducted in controlled laboratory settings. In the following sections, we will provide details about foundational research on retrieval practice and recent cutting-edge research, showing the relevance of retrieval practice for cognitive science and education. We also discuss theories proposed to explain retrieval practice effects of retrieval practice on memory and highlight key issues for future research.

FOUNDATIONAL RESEARCH

As we noted, the fact that retrieval improves learning was acknowledged before the advent of experimental research on learning and memory. In

Novum Organum (1620), Francis Bacon wrote about the benefits of retrieval for learning: "If you read a piece of text through twenty times, you will not learn it by heart so easily as if you read it ten times while attempting to recite from time to time and consulting the text when your memory fails" (p. 143). In the *Principles of Psychology* (1890), William James wrote: "A curious peculiarity of our memory is that things are impressed better by active than by passive repetition. I mean that in learning (by heart, for example), when we almost know the piece, it pays better to wait and recollect by an effort from within, than to look at the book again. If we recover the words in the former way, we shall probably know them the next time; if in the latter way, we shall very likely need the book once more" (p. 646).

Both Bacon and James captured the essence of retrieval-based learning, and early experiments carried out a century ago demonstrated the basic effect (Abbott, 1909). Gates (1917) carried out perhaps the first large-scale study of retrieval practice. He had groups of children from first to eighth grade study nonsense syllables (the classic material used by Ebbinghaus, 1885, in his memory experiments) and brief biographies taken from *Who's Who in America*. The children were presented with a two-phase study procedure: in the first phase, they simply read the material, and in the second phase they were instructed to look away from the materials and try to retrieve the information by themselves, checking the material when necessary (Gates called this procedure *recitation*). Gates manipulated the proportion of time spent retrieving—0, 20, 40, 60, 80, or 90% of the total time spent in the study procedure. The total time spent in the study procedure was the same for all the conditions. After the study procedure, Gates gave all the children a test in which they were supposed to recall all the studied items in order. Three to four hours after the first test, all the children received a second test. Gates's (1917) basic results indicated that the more time the children spent retrieving, the better they performed on the final tests, especially on the delayed test (see Roediger & Karpicke, 2006a, for a detailed discussion of Gates's experiments).

After Gates (1917), the beneficial effects of retrieval on learning were replicated several times (e.g., Jones, 1923–1924; Spitzer, 1939). However, after the 1940s, interest on the effects of retrieval on learning seemed to vanish, and we can only speculate why. The 1950s and 1960s were the heyday for the study of forgetting (Crowder, 1976), and a premium was placed on using the best methods to study the time course of forgetting. The appropriate way to measure forgetting is to test different people or different sets of materials at different points in time. Repeatedly testing the same person over the same materials would lead to incorrect forgetting measures, because each act of retrieval influences subsequent retrieval. The contaminating effects of one test on another were noted in influential textbooks by McGeoch

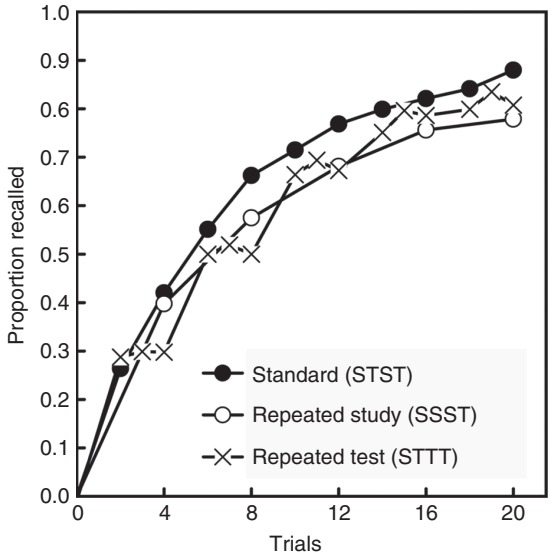

Figure 1 Proportion of words recalled during the learning trials, by condition. Data adapted from a replication of Tulving (1967) conducted by Karpicke and Roediger (2007, Experiment 1). The learning curves do not differ by condition, indicating that test episodes lead to at least as much learning as study episodes.

(1942) and Deese (1958). Thus, the standard procedure to study retrieval practice effects—testing the same person or the same sets of materials repeatedly—may have been seen as a nuisance, rather than an interesting phenomenon to be studied in its own right (Karpicke, Lehman, & Aue, 2014).

A second wave of interest in the effects of retrieval on learning occurred in the late 1960s and early 1970s. The impetus for this renewed interest was most likely a paper by Tulving (1967) that examined the role of encoding (study) and retrieval (test) opportunities during list learning. Tulving (1967) had subjects learn word lists across alternating study and recall trials. In a standard learning condition, subjects studied, recalled, restudied, recalled again, and so on, for an equal number of alternating study and recall trials (labeled STST in Figure 1). In a second condition, Tulving increased the number of study trials, so that the subjects studied three times and then recalled within each cycle of 4 trials (labeled SSST). Finally, in a repeated test condition, Tulving had subjects study and then recall three times on three consecutive tests (STTT). If subjects learned only during study trials, then the repeated study (SSST) condition should produce dramatic improvements in learning, and the repeated test (STTT) condition would be at a great disadvantage, because that condition experienced fewer study trials. Surprisingly, performance was roughly the same for the three conditions. Figure 1 shows data from a replication of

Tulving's (1967) experiment conducted by Karpicke and Roediger (2007). The learning curves under the standard, repeated study, and repeated retrieval conditions looked remarkably similar. The implication is that learning must be occurring during the test trials, just as it occurs during study trials.

Although interest in retrieval or testing effects was renewed after Tulving's (1967) paper, it seemed to die away quickly in the early 1970s (although there are notable exceptions to this general statement; e.g., Landauer & Bjork, 1978; Masson & McDaniel, 1981). Again, one can only speculate why interests shifted, but memory research in the 1970s was dominated by the emergence of levels of processing (Craik & Lockhart, 1972) and encoding specificity (e.g., Tulving & Thomson, 1973). Perhaps most importantly, the brief renewal of interest in retrieval practice in the 1970s did not appear to be integrated with educational applications. At around the same time, there was interest in adjunct questions (e.g., Anderson & Biddle, 1975), which certainly shares some similarities with retrieval practice research in the sense that both use retrieval as a learning strategy, but the two camps were never truly integrated.

The third wave of interest in the mnemonic effects of retrieval began about a decade ago. One of the studies that helped to stimulate research on retrieval practice was done by Roediger and Karpicke (2006b), and was modeled on the work done a few decades before, especially the work of Hogan and Kintsch (1971). Roediger and Karpicke (2006b) examined the effects of retrieval practice on the learning of short educational texts on science topics. They created three conditions that varied the number of study and retrieval periods but held total time constant: a study-only condition in which students read the text in four study periods (SSSS); a condition in which subjects read the text three times and then were asked to retrieve the text once (SSSR); and a third condition in which students studied the text once and then were asked to retrieve the text three times (SRRR). During retrieval periods, students were asked to recall as many ideas as they could from the text, and they did not reread or receive feedback. After this procedure, subjects were asked to predict how well they thought they would remember the text after 1 week (a judgment of learning; see Dunlosky & Metcalfe, 2009). One week after the initial learning phase the subjects returned to the lab and were asked to retrieve the text again, as a measure of retention of the materials after a delay. The results, as depicted in Figure 2, showed that more retrieval practice (in the SRRR condition) produced the best performance on the delayed final test. However, subjects' judgments of learning were based on the number of study episodes and not retrieval episodes; i.e., more study episodes led students to believe they had learned the most, even though the opposite was true.

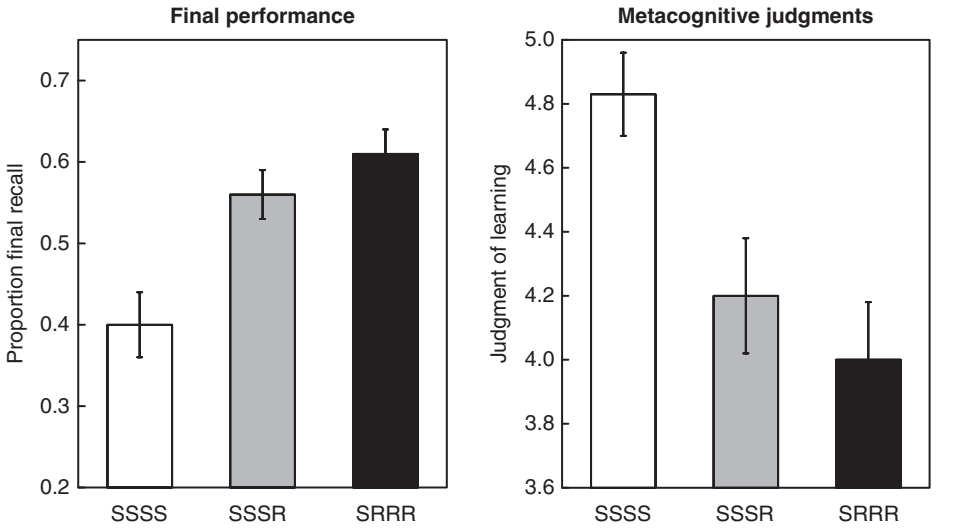

Figure 2 Final recall on a 1-week delayed test and judgments of learning by condition: SSSS (four repeated study periods); SSSR (three repeated study periods followed by one retrieval period), and SRRR (one study period followed by three repeated retrieval periods). Judgments of learning were made on a 7-point scale, where 7 indicated that students believed they would remember material very well. Data adapted from Roediger and Karpicke (2006, Experiment 2). More retrieval periods produced the best performance, whereas judgments of learning were mostly influenced by the number of study periods.

As of the writing of this essay, the Roediger and Karpicke (2006b) paper has been cited over 800 times, and Roediger and Karpicke's (2006a) review article has been cited over 700 times, according to Google Scholar. These citation counts reflect the surge in interest in retrieval practice that has occurred over the past 9 years. A complete review of the retrieval practice literature is beyond the scope of this essay. The next section provides a selective review of recent research on retrieval practice.

CUTTING-EDGE RESEARCH

Contemporary research on retrieval-based learning has generally pursued two objectives: deepening our theoretical knowledge about retrieval practice, and identifying ways to apply retrieval practice in educational settings. Some research has attempted to meet both objectives at the same time, and this research would be placed in "Pasteur's quadrant," according to the framework defined by Stokes (1997). Stokes (1997) encouraged researchers to conceptualize theoretical advancement and practical application as two dimensions of research, and a research project might be high or

low on each dimension. We describe Stokes' ideas because it provides a framework for understanding current research on retrieval-based learning. Advancing theoretical knowledge and developing education applications of retrieval-based learning are both important objectives. We discuss recent theoretical advancements first.

Theoretical Advancements

A number of theoretical accounts of the mnemonic benefits of retrieval have been presented. Those accounts include the idea that retrieval strengthens memory traces (Bjork, 1975), that effortful retrieval is especially important for promoting learning (Bjork, 1994; Pyc & Rawson, 2009), and that retrieval practice provides training in the same processes that will be required on a later criterial test, so performance is improved via transfer-appropriate processing from practice to a final test (e.g., Kolers & Roediger, 1984; Roediger & Karpicke, 2006a). Karpicke, Lehman, and Aue (2014) recently provided a comprehensive overview of theories of retrieval practice and noted that there are two main accounts that propose possible *mechanisms* of retrieval-based learning: the elaborative retrieval account and the episodic context account.

Carpenter (2009) has championed the elaborative retrieval account, which proposes that semantic elaboration occurs during the process of retrieval and that will increase the probability of later recall. More specifically, when subjects retrieve a given response, several items that are semantically related to the retrieval cues become activated. Carpenter (2009) had subjects learn cue-target pairs, either by rereading the pairs or taking a cued recall test in which they were presented with the cue and had to retrieve the target. The cue and the target could be strong associates (e.g., *toast-bread*) or weak associates (e.g., *basket-bread*). Carpenter's results showed the usual benefit of retrieval practice on a final criterial test and larger retrieval practice effects for weak associates than for strong associates.

According to the elaborative retrieval theory, these results point to the idea that while trying to recall *bread* when given a weakly associated cue such as *basket*, several other words that are semantically associated to *basket* become active (*eggs*, *fruit*, etc.). Then, on a final criterial test, these elaborations (*eggs*, *fruit*, etc.) can be used as retrieval routes to the target *bread*. The theory assumes that when more retrieval routes were activated via semantic elaboration, a person would be more likely to retrieve the target word. So, when the initial retrieval cue was a weak associate to the target word there was more elaboration and therefore more positive effects of the retrieval on a later test than when the initial retrieval cue was a strong associate of the target word. Basically, according to the elaborative retrieval account,

subjects elaborated by bringing to mind several related words, and this promoted later retention.

Karpicke *et al*. (2014) noted a number of limitations of the elaborative retrieval account, including the fact that direct attempts to induce elaboration have not produced learning gains like those produced by retrieval practice (Karpicke & Smith, 2012). As an alternative, Karpicke *et al*. proposed an episodic context account of retrieval-based learning. Briefly, the episodic context account proposes that when learners retrieve knowledge, they reinstate a prior context in which the information was learned. When retrieval is successful, the context associated with that knowledge is updated, and the updated context is used to enhance subsequent retrieval. Karpicke *et al*. reviewed research that supports the context account, and we describe a few critical examples.

Karpicke and Zaromb (2010) carried out a series of experiments that showed the importance of remembering an initial study context above and beyond merely generating knowledge. At a first glance, active retrieval could seem very similar to other learning activities that required active generation of knowledge, but the results obtained by Karpicke and Zaromb indicate otherwise. They presented subjects with a list of target words (e.g., *love*) and then, in a second phase, a previously presented target word could either be paired with a cue (e.g., *heart—love*) or be paired with a cue and a fragment of the target (e.g., *heart—l_v_*). When the target word was presented intact, subjects only had to read the pair (Read condition), but when the target word was presented as fragment, subjects could either be instructed to complete the fragment with the first word that came to mind that successfully completed it (Generate condition) or to use the fragment as a cue to help them remember a word that was presented in the initial phase (Recall condition). The Recall condition involved remembering the prior context, whereas the Generate condition did not. Finally, in a third phase, subjects were given a criterial test, in which they had to recall (or recognize) the target words.

Figure 3 shows the results of one of Karpicke and Zaromb's experiments. Performance on the criterial test was consistently better in the Recall condition than it was in the Generate condition. Importantly, performance in the second phase of the experiments was the same for the generate and the recall conditions (about 75%), indicating that differences on the final criterial test were not due to differences in the number of items retrieved during the second phase. These results are particularly important because what differentiated the Generate and the Recall conditions was purely the instructions given to subjects, which points to the importance of active retrieval and the functional value of putting subjects in a retrieval mode. When the active reconstruction of the context of a previous event occurs, the probability that it

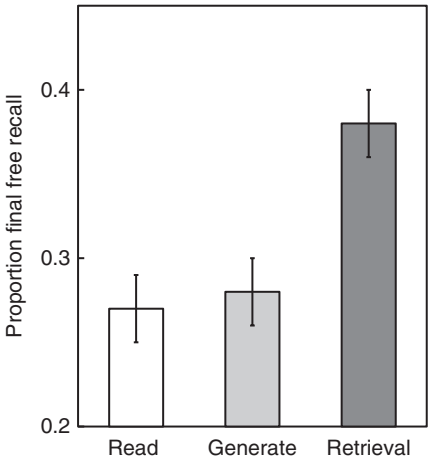

Figure 3 Final recall by condition: Read, Generate, and Retrieval. Data adapted from Karpicke and Zaromb (2010). Intentionally retrieving words enhanced performance in a criterial test in comparison to rereading words whereas generating words did not improve performance in comparison to just rereading the words.

will occur in the future is high, and therefore it is adaptive to enhance the process by which it occurs. Thus, context reinstatement facilitates future memory performance.

Karpicke *et al*. (2014) outlined a variety of evidence that supports the context account, including the findings that retrieving episodic context promotes learning (e.g., Karpicke & Zaromb, 2010) and that practicing retrieval improves one's ability to recollect context on a criterial test (e.g., Chan & McDermott, 2007; Lehman, Smith, & Karpicke, 2014). The episodic context account provides a viable account of retrieval-based learning. The account also has possible implications for education, because the locus of retrieval practice effects is in remembering a prior study context. Therefore, educational activities that may not require learners to remember a prior context can be "converted" into retrieval-based learning activities simply by requiring students to complete the activities in the absence of to-be-learned materials (Blunt & Karpicke, 2014). In the next section, we turn to some recent developments in the application of retrieval-based learning to educational materials and classroom settings.

Educational Applications

Conducting research at the interface between cognitive science and education is challenging and rewarding. To integrate findings from cognitive science with educational practice, at a minimum, researchers must use

authentic educational materials, tasks that would be plausible in educational settings, and assessments that are relevant to real-world learning outcomes. Our view is that cognitive scientists should consider educational goals first and look for opportunities where ideas from cognitive science might help, rather than only conducting cognitive experiments that might be applied to education in unspecified ways.

Karpicke and Blunt (2011) carried out two experiments that were aimed at meeting some of the criteria laid out above. They had subjects read educational texts and then either practice retrieval of the material without looking at the text or create an organizational diagram called a *concept map*. Concept mapping is a popular educational activity where students have to connect concepts by drawing a diagram and focus on the organization of the material and the relation between concepts (Novak & Gowin, 1984). Karpicke and Blunt included two additional conditions, in which students read the material once or repeatedly but completed no other activity. At the end of the learning phase, the students indicated how well they thought they would remember the material 1 week later, and they then returned after 1 week for a final short-answer assessment. Importantly, the final assessment included conceptual questions that required the students to make inferences about what they had learned, in addition to remembering the content. Figure 4 shows that students in the retrieval practice condition performed best on the final test, even better than students who spent time completing the elaborative concept mapping activity. Interestingly, students consistently believed that they had learned more after the concept mapping activity than after practicing retrieval (see too Roediger & Karpicke, 2006b). Moreover, in a second experiment, Karpicke and Blunt showed that students who practiced retrieval performed better than students who created concept maps even when the final test involved creating a concept map.

Karpicke and Blunt (2011) showed large benefits of retrieval practice with educational texts, relative to a widely used educational activity, as measured on an assessment of meaningful learning. The Karpicke and Blunt experiments also support the idea that elaborative encoding and retrieval practice activities may promote learning via different mechanisms (see too Karpicke & Smith, 2012). Subsequent experiments showed that concept mapping can be effective when it is completed as a retrieval-based activity (Blunt & Karpicke, 2014). Altogether, the results provide an important demonstration of the effectiveness of retrieval-based learning with educational materials.

Recent work has sought to include the features described earlier—educational materials, plausible activities, and meaningful assessments—in research conducted in classroom settings. One example comes from McDaniel, Thomas, Agarwal, and Roediger (2013), who explored the effects of frequent quizzing as a retrieval activity in the classroom. McDaniel and

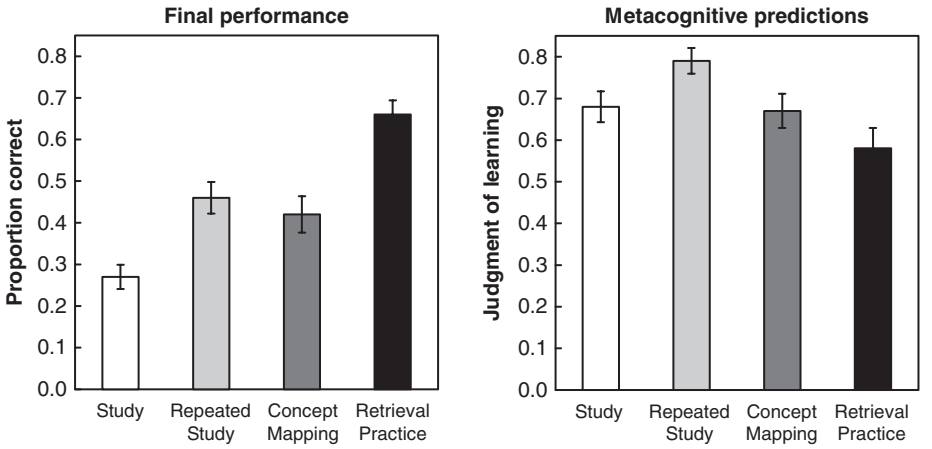

Figure 4 Final performance on verbatim questions following a 1-week delay and judgments of learning by conditon: Study (one study period); Repeated Study (four study periods); Concept Mapping (one study period followed by elaborative concept mapping); and Retrieval Practice (two cycles of one study period followed by one retrieval period). Data adapted from Karpicke & Blunt (2011, Experiment 2). Practicing retrieval enhanced performance relative to elaborative concept mapping and study only conditions, but judgments of learning did not reflect this.

colleagues tested the effectiveness of quizzing middle-school students in their science classes, using chapters from their textbook as materials. Within the same science unit, the students were quizzed over some concepts but not over other concepts. There were a total of three quizzes, one before the lesson but after reading the assigned chapter, another after the lesson, and one review quiz 24 hours before the exam. The end-of-chapter exam occurred approximately 11 days after the materials were first introduced. On the end-of-chapter exam, students performed better on the topics that had been quizzed than on the non-quizzed topics. Moreover, the benefits of quizzing extended to items that required transfer of knowledge, that is, items that were not exactly identical to the ones quizzed in class (see also Butler, 2010).

The work by McDaniel *et al*. (2013) shows how our existing knowledge about retrieval practice can be directly integrated within real-world classroom learning. The research also provided new knowledge about how retrieval practice with application questions was especially effective for promoting long-term retention and comprehension of middle-school science topics. Ultimately, integrating theoretical developments about the nature of retrieval practice with educational applications will help identify the most effective and feasible ways to implement retrieval-based learning activities in classroom settings.

KEY ISSUES FOR FUTURE RESEARCH

The key issues for future research on retrieval-based learning are related to deepening theoretical knowledge and simultaneously identifying the most effective and feasible ways to integrate that knowledge in educational settings. Thus, researchers should aim to situate future research squarely within "Pasteur's quadrant" (Stokes, 1997) so that it advances both theoretical and practical knowledge. Research on retrieval practice has surged over the past decade, but the field is still far from having a well-developed, mechanistic theory. The episodic context account (Karpicke *et al*., 2014) seems promising because it explains the key effects in the retrieval practice literature and accounts for effects that are difficult for other theories to handle. However, the predictions of the episodic context have not been fully specified and rigorously tested. In addition, although the episodic context account is based on assumptions form a variety of memory models, the account itself still remains to be implemented in a formal model, which will advance theoretical and empirical progress.

An important feature of the episodic context account is that it clearly identifies repeated, successful retrieval as the locus of retrieval-based learning. Retrieval does not exclusively occur during "tests"—indeed, retrieval can occur in a wide variety of activities that prompt students to remember prior learning episodes. This general perspective can guide future research on the best ways to design retrieval-based learning activities for students. Many educational activities can be modified to incorporate active retrieval, for instance, as Blunt and Karpicke (2014) showed by modifying concept mapping to involve retrieval practice. On the other hand, it is also important to note that not all tests involve retrieval, in the sense of remembering a prior episodic context. The emphasis on "testing" and "testing effects" may obscure that the locus of the effect is active retrieval. This distinction is important because it focuses theorizing on retrieval mechanisms and it clarifies how educational activities might be designed to improve learning.

Finally, it is important to develop activities that encourage retrieval practice because, in general, many students are not aware of the large benefits of practicing retrieval (Karpicke, Butler, & Roediger, 2009). Many experiments have shown that when students make judgments of learning, their judgments do not reflect the fact that practicing retrieval would promote long-term learning (Figures 2 and 4). Thus, in addition to much needed theoretical developments, it will be necessary to continue identifying the most effective ways to guide students to practice retrieval not only in the classroom but also when they study on their own.

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