Is Retrieval Practice Always Superior to Restudy?

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Abstract

A classic study by Roediger and Karpicke (2006a) investigated the relative benefits of restudy versus retrieval practice, or “test”, on memory retention. Repeated studying was superior to repeated testing when memory was tested immediately (all study > multiple study/single test > single study/multiple tests). Strikingly, the pattern reversed when memory was tested after a days-long delay, with best performance in a single study/multiple tests condition. As each study period was minutes-long and contained repeated reading of a to-be-remembered text passage, we were interested whether the striking benefit for repeated testing at the expense of any restudy replicates when study opportunities are brief, akin to a single mention of a fact in a lecture. Participants encountered academically relevant facts a total of three times, each time either studied (S) or self-tested (T). Final test followed immediately or after a delay (Experiment 1: two days, Experiment 2: seven days). Partially replicating prior work, immediate memory benefited from repeated study ($SSS > SST > STT$), but the pattern did not reverse after a delay. Instead, memory was superior for facts the were restudied in addition to self-tested ($SST > STT = SSS$). We further investigated whether restudy after a test (STS) provides additional benefits compared to restudy before test (SST), but found comparably high delayed recall in both conditions. The results show that under some circumstances, balancing repetition and testing can allow for more information to be learned and retained long-term.

Keywords: retrieval practice, testing effects, retention, long-term memory, forgetting

Is Retrieval Practice Always Superior to Restudy?

Factors that help us encode information into long-term memory and reduce forgetting have been of major interest in memory research. Seminal work by Ebbinghaus (1964) examined how restudying material affected long-term memory retention and forgetting over time. He showed that the rate of forgetting is especially rapid early after learning, but repeated study reduces forgetting. Many have examined this repetition effect in other memory paradigms and confirmed that increasing study repetitions results in more accurate recall (Bromage & Mayer, 1986; Mayer, 1983; Webb, 2007) and recognition (Davis, Lockhart, & Thomson, 1972; Donaldson, 1981) memory performance.

In addition to repetition, retrieval practice has also been shown to boost memory performance (Gates, 1917; Hogan & Kintsch, 1971; Spitzer, 1939; Tulving, 1967). A common way to induce retrieval practice is by testing the to-be-remembered material after its initial study, with the term *retrieval practice effect* or *testing effect* referring to the increased memory retention after retrieval compared to studying alone. Retrieval practice benefits memory, even when it comes at the expense of repetition. For example, Roediger and Karpicke (2006a) had participants either study prose passages twice (SS) or study once and practice retrieval once via free recall (ST) without corrective feedback. After a delay, participants were given a final free-recall test to assess long-term retention. After intervals of 2-days and 1-week, participants who practiced retrieval without feedback had better memory retention than participants who studied twice as much without an opportunity for retrieval practice ($ST > SS$). This phenomenon has been replicated numerous times, demonstrating that retrieval of material with and without feedback strengthens subsequent memory (see for review and meta-analyses Adesope, Trevisan, & Sundararajan, 2017; Roediger & Butler, 2011; Rowland, 2014).

When there are multiple opportunities for study or test, repeated testing seems to provide additional benefits. In the same study by Roediger and Karpicke (2006a), participants were given prose passages and instructed to read and study for the duration of a five-minute period. Additional five-minute periods were filled with either more study time (S) or with test time (T) where participants tried to retrieve as much of the passage as possible without an opportunity to re-read it or receive feedback on their recall. After a five-minute delay, participants who only had the initial study period followed by multiple test periods (STTT) recalled the least amount of detail, with more study time being associated with better performance ($STTT < SSST < SSSS$). In contrast, when retrieval was tested after a week-long delay, the pattern of results reversed, with repeated testing being associated with better performance than repeated study ($STTT > SSST > SSSS$). Furthermore, it appeared that repeated testing also minimized forgetting – comparable performance was seen in the STTT condition tested after five minutes as when tested after a week, while performance was lower after a week in all other conditions (Roediger & Karpicke, 2006a). Thus, although a limited amount of information was encoded in the single study period, as evidenced by lower STTT performance in the five-minute delay condition, almost all that was encoded was resistant to forgetting over a period of a week, due to repeated testing.

But should all study repetition be replaced by testing to maximize long-term memory? While past work has shown that replacing repetition with testing better prevents forgetting of the initially learned items, there are limitations. Given that only a fraction of information will be remembered after a single encounter, one could conclude that including some repetition may provide greater memory retention overall as much may be missed with such little initial exposure. Indeed, it is important to note that even in the single study conditions discussed

above, participants typically had multiple opportunities to study each piece of information. For example, in Roediger and Karpicke (2006a), the study period was fixed at five minutes rather than one read-through of the passage. Thus, participants had an opportunity to re-read the text passage several times within that period. In Karpicke and Roediger (2007), another study that found a benefit of repeated testing over repetition, each word-list study cycle consisted of five passes through the list, so participants in the single study condition (STTT) actually studied each word-list five times (and 15 times in the SSST condition). Thus, the *combination* of repetition and retrieval practice in these conditions may be critical for long-term retention, rather than repeated testing alone. The first goal of the current study was to test to what degree replacing repetition with repeated retrieval practice affects learning and retention under more extreme conditions where material is briefly encountered, akin to a mention of a fact during an academic lecture. Because limited information can be remembered after a single exposure, we hypothesized that balancing testing with repetition may be more beneficial than multiple test opportunities.

To test this hypothesis, we conceptually followed the seminal study by Roediger and Karpicke (2006a), testing immediate and delayed memory after varying repetition and retrieval attempts while keeping the overall time with the material constant. Here, participants encountered academically relevant stimuli (facts from a range of disciplines) three times each, either complete (study, S) or with a missing word that they covertly attempted to retrieve (self-test, T). The degree of study and self-test opportunities varied across stimuli in a within-subject design, such that after the initial study, some of the facts were restudied twice (SSS condition), some were restudied once and self-tested once (SST condition) and some were not restudied but instead were self-tested twice (STT condition). As feedback would provide an extra study

opportunity (e.g., making an SST condition effectively an SST(S) condition) and make interpretation unclear (Greving & Richter, 2018), potentially conflating retrieval practice effects with test-potentiated learning effects (Arnold & McDermott, 2013), no feedback was provided (Nungester & Duchastel, 1982; Roediger & Karpicke, 2006a; Verkoeijen, Bouwmeester, & Camp, 2012). To assess the effects of retrieval practice and repetition on learning and long-term retention, half of the participants completed the final test on the same day, while the other half completed the final test after a delay of two days (Experiment 1) or one week (Experiment 2).

In addition to improving retention, testing has also been reported to boost the efficiency of subsequent opportunities to restudy material (Hays, Kornell, & Bjork, 2013; Izawa, 1966, 1970; Karpicke & Roediger, 2007; Kornell, Hays, & Bjork, 2009). This *test-potentiated learning effect*, or *indirect testing effect*, is present even when a previous retrieval attempt is unsuccessful and when no corrective feedback on the retrieval is provided (Arnold & McDermott, 2013). For this reason, Arnold and McDermott (2013) argue that studies showing greater retrieval practice effects when including feedback may be instead demonstrating the powerful combined effects of both retrieval practice effects and test-potentiated learning effects. To explicitly assess test-potentiated learning, several studies have intentionally incorporated conditions that include restudy after test (Dirkx, Kester, & Kirschner, 2014; Karpicke & Roediger, 2007; van Gog & Kester, 2012). However, Arnold and McDermott (2013) argue that test-potentiated learning in some studies may be difficult to disentangle from retrieval benefits per se. For example, Dirkx and colleagues (2014) found better delayed performance in STST compared to SSSS, which could be due to retrieval practice or enhanced restudying of material after testing. Karpicke and Roediger (2007) held the number of study and retrieval opportunities equal between conditions and still found a benefit for restudy after test (STST > SSTT). However, the benefit of the STST

condition could be both due to more efficient restudy after test (enhanced second study) and because more material was strengthened by a second retrieval attempt after restudying (additional higher benefit of the second test).

Importantly, even without the conflation with the final retrieval attempt, one may expect that the order of restudy and test may affect long-term memory. For example, retrieval attempts, even when unsuccessful, can make subsequent study more effective (Kornell, 2014; Kornell et al., 2009; Richland, Kornell, & Kao, 2009), which could provide a benefit for an STS over SST study protocol. Furthermore, the order of study and test opportunities should also matter when one considers the bifurcation model of testing effects, proposed by Kornell and colleagues (2011). In the bifurcation model, restudy leads to a small increase in memory strength for all material, resulting in a shift of the whole distribution of memory strengths. In contrast, testing leads to a higher increase of memory strength, but only for items that are already above retrieval threshold, leading to a “bifurcated” (split) distribution of memory strength as items currently below retrieval threshold remain unstrengthened. Because the retrieved memoranda end up far above threshold (much further than they would be after re-study), they will tend to remain above threshold longer than restudied ones. Within this framework, both SST and STS training would be expected to lead to bifurcated distributions, but with a greater proportion of items in the high memory strength (bifurcated) part of the distribution in the SST condition. This would potentially lead to greater resistance to delay-related performance decline in the SST than STS condition. Thus, the second objective of the current study was to examine the potential cost or benefit of restudying material after retrieval practice. To achieve this objective, we compared immediate and delayed performance in the SST condition with an STS condition, where a restudy opportunity followed a retrieval opportunity. Because retrieval attempts can make

subsequent study more effective (Kornell, 2014; Kornell et al., 2009; Richland et al., 2009), we hypothesized that restudying after testing (STS) may boost learning and long-term retention to a greater degree than restudying before testing (SST).

Method

The two experiments described below had identical methods except for the length of delay in the Delay condition (Experiment 1 = 2 days; Experiment 2 = 7 days). Because the pattern of results was the same across experiments, we report both experiments jointly for brevity and clarity, but the same conclusions would be reached by considering each experiment separately.

Participants

Participants were recruited from the University of Oregon community via the university SONA research system. Data were collected from 66 participants in Experiment 1 and 72 participants in Experiment 2. All participants provided written informed consent and received US \$25 compensation for their participation across two experimental sessions. All experimental procedures were approved by Research Compliance Services at the University of Oregon. Participants were either native English speakers or had a high level of English language proficiency. Participants recruited for Experiment 2 were verified to have not participated in Experiment 1. One participant was excluded from each experiment for poor performance, indicated by overall accuracy three standard-deviations below the group mean. This left 65 participants from Experiment 1 ($M_{\text{age}} = 21.9$, $SD_{\text{age}} = 3.6$, age range: 18-33, 41 females, 24 males) and 71 participants from Experiment 2 ($M_{\text{age}} = 20.1$, $SD_{\text{age}} = 2.3$, age range: 18-32, 54 females, 17 males) for analyses.

Stimuli

Factual statements were used as stimuli to examine the retrieval-practice effects in an academically relevant context. Each statement had two formats: a study format and a test format. Statements in the study format consisted of complete, factual statements aggregated by the research team from a range of disciplines: art, astronomy, biology, chemistry, geography, health, world history, literature, music, mythology, neuroscience, perception, physical science, religion, sports, theater, and world travel. Statements in the test format were the same as those used in study except that one keyword from the original study statement was replaced with a “_____” (blank). See Figure 1 for an example study and test trial. Test statements were used to induce retrieval practice during the training portion of the experiment and used in the final test phase described below.

Figure 1. Sample stimulus from study and test experimental blocks. Participants were given a cue at the beginning of each experimental block to signal whether items to come would be studied or self-tested.

Procedure

All participants enrolled in a two-session experiment with a two-day (Experiment 1) or seven-day (Experiment 2) delay between sessions. Participants first underwent training during Session 1, learning a series of facts presented on a computer screen in MATLAB using The Psychophysics Toolbox (Brainard, 1997). From a larger bank of 202 factual statements, 150 statements were randomly selected for each participant and randomly assigned to one of four training conditions or one “never-studied” condition (30 statements per condition). Statements assigned to the never-studied condition were not presented during training; instead, their inclusion in the final test served two purposes. First, it allowed us to estimate individuals’ prior knowledge, providing a baseline. Second, as the immediate group would be taking their final test at the end of an hour-long experimental session and the delay group would be taking their final test on a new day without any prior testing, comparing performance between groups for the never-studied items would allow us to control for any group differences unrelated to learning, such as fatigue.

The training consisted of 12 blocks (Figure 2). Each block contained either 30 study or 30 self-test trials from one condition, with all trials separated by a two-second interval. During *study* trials (Figure 1, left), participants were shown a factual statement and asked to study and memorize the sentence to the best of their ability (6s). Participants were then presented with two response options on the screen (2s), where they were asked to make a prospective memory judgment (e.g., “will remember” or “may remember”) indicating their confidence in recalling the statement later. Prospective memory judgements were not analyzed and only included to facilitate engagement with the task as pilot testing indicated that the observational nature of the task would otherwise result in fatigue and disengagement. A third response option (“already

knew”) was included during the initial study phase so that participants could indicate if they already knew the presented fact prior to participating in the experiment. This option was included to allow us to estimate prior knowledge and focus analyses on facts learned during the course of the experiment. During *test* trials (Figure 1, right), participants were shown the same statements (6s), but with one of the key terms missing and replaced by a “_____” (blank). While some work suggests that testing effects are larger using overt retrieval practice techniques (Jonsson, Kubik, Sundqvist, Todorov, & Jonsson, 2014; Experiment 1 from Tauber et al., 2018), several studies also demonstrate that overt and covert retrieval methods provide similar benefits to long-term retention (Putnam & Roediger, 2013; Smith, Roediger, & Karpicke, 2013; Sundqvist, Mäntylä, & Jönsson, 2017; Experiment 2 from Tauber et al., 2018). To simplify our experimental design, and because studies have demonstrated the efficacy for both overt and covert retrieval practice, we opted for a covert approach and asked participants to self-test and mentally fill-in-the-blank by retrieving the correct keyword from memory, without vocalizing or writing down their response. Participants then indicated how successful they were in recalling the missing keyword (2s) by choosing from three response options: definitely remembered, maybe remembered, did not remember.

In all training conditions, each statement was encountered three times in a study or self-test format. Trials were blocked by condition and repetition (Figure 2). The first presentation of a statement was always in a study format. Training conditions differed in the format of subsequent encounters of the statements assigned to that condition. After the first study block of each condition was completed, training continued with a second block from each condition (in a study or test format) and then third block of each condition (in a study or test format). In the SSS condition, all blocks were in study format; in the SST condition, the last study block was

Condition	Presentation 1	Presentation 2	Presentation 3	Final Test
SSS	Study	Study	Study	The optic nerve is composed of the _____ of ganglion cells.
	The optic nerve is composed of the axons of ganglion cells.	The optic nerve is composed of the axons of ganglion cells.	The optic nerve is composed of the axons of ganglion cells.	
SST	Study	Study	Test	Romanesque and _____ are two styles of cathedral.
	Romanesque and Gothic are two styles of cathedral.	Romanesque and Gothic are two styles of cathedral.	Romanesque and _____ are two styles of cathedral.	
STS	Study	Test	Study	Robert Frost recited a poem at the inauguration of President _____.
	Robert Frost recited a poem at the inauguration of President Kennedy.	Robert Frost recited a poem at the inauguration of President _____.	Robert Frost recited a poem at the inauguration of President Kennedy.	
STT	Study	Test	Test	The _____ empire occupied Russia for 240 years.
	The Mongol empire occupied Russia for 240 years.	The _____ empire occupied Russia for 240 years.	The _____ empire occupied Russia for 240 years.	
Never- Studied	no study or self-test			_____ gives Mars its notorious red hue.

Day 1
Day 1 or 2

Figure 2. Structure of training conditions and sample stimuli. Full stimulus set is available on the Open Science Framework (see open practices statement at end of manuscript for link).

replaced by a self-test block; in the STT condition, the second and third block were in test format. We also included the STS condition, that we compared to the SST condition to test our hypothesis that having the opportunity to restudy material after test (STS) would provide additional long-term memory benefit compared to restudying material before test (SST). The order of presentation of the blocks from the four training conditions was counterbalanced using a Latin Square design, so each condition appeared equally often in all serial positions. Each block was approximately five minutes in length, making the total training phase time approximately 60 minutes. Participants were given opportunities to take self-paced breaks after each block to reduce fatigue.

After completion of the computerized training phase, participants were given a written final test containing 150 test items: 120 statements from training and 30 new statements that

were never studied. They were asked to write down (by hand) the missing keyword from memory to accurately complete each statement. Participants randomly assigned to the immediate final test condition (Experiment 1: $n = 31$, $M_{\text{age}} = 21.3$, $SD_{\text{age}} = 3.3$, age range: 18-31, 21 females, 10 males; Experiment 2: $n = 38$, $M_{\text{age}} = 20.3$, $SD_{\text{age}} = 2.2$, age range: 18-29, 31 females, 7 males) were given the written test during session one, immediately after completion of the computerized learning task. Participants assigned to the delay final test condition (Experiment 1: $n = 34$, $M_{\text{age}} = 22.3$, $SD_{\text{age}} = 3.8$, age range: 19-33, 20 females, 14 males; Experiment 2: $n = 33$, $M_{\text{age}} = 19.9$, $SD_{\text{age}} = 2.5$, age range: 18-32, 23 females, 10 males) completed the final written test during their second session, two days later in Experiment 1 or seven days later in Experiment 2. Although participants assigned to the immediate group had already taken their final written test during the first session, they were also brought back to the lab for a second session and completed unrelated tasks to avoid a self-selection bias for a two-session versus single-session study.

Results

The facts that participants endorsed as already known to them ($M = 21\%$, $SD = 12\%$) were excluded from subsequent analyses to focus on memory for facts learned within the course of the experiments. Participants' self-report was a meaningful indicator of their prior knowledge as their final recall of those facts was 80%, compared to 59% recall for facts they did not endorse as already known during study ($t(133) = 18.80$, $p < 0.001$, $d = 1.62$). All results replicate when memory for all studied facts is analyzed instead. Participants learned new information over the course of the experiment beyond their prior knowledge, as they were able to fill-out only 11% of blanks for never-studied items during final test.

The Effect of Repetition vs. Retrieval Practice

The main question of our study was whether the striking benefit of replacing all repetition with retrieval practice (delayed recall $STTT > SSST > SSSS$), reported by Roediger and Karpicke (2006a), replicates for briefly presented facts. Mean recall for facts encountered in SSS, SST and STT conditions in each group is presented in Figure 3. The recall scores were submitted to a 3 x 2 x 2 repeated measures ANOVA, with study condition [SSS, SST, STT] as a within-subject factor and group [immediate, delay] and experiment [Experiment 1, Experiment 2] as between-subject factors. Full ANOVA results are reported in Table 1. Although there was a main effect of experiment, reflecting better recall for the shorter delay period in Experiment 1 ($M_{\text{recall}} = 60\%$, 95% CI [56.7 - 63.3%]) than Experiment 2 ($M_{\text{recall}} = 54\%$, 95% CI [50.3 - 56.6%]), experiment factor did not interact with any effect of interest. We thus retained the joint report of the data for brevity, verifying that the same pattern of results is present in each experiment separately.

Figure 3. Mean cued recall during immediate (solid lines) and delayed (dashed lines) fill-in-the-blank recall test. Black lines represent data from Experiment 1 (delayed test after 2 days), gray lines represent data from Experiment 2 (delayed test after 7 days). Error bars denote standard error of the mean.

Table 1

Effect of Repetition and Retrieval Practice, Repeated Measures ANOVA Results.
Condition (SSS, SST, STS) x Group (Immediate, Delay) x Experiment (Exp 1, Exp 2)

Effect	df	F	p	η_p^2
Study Condition*	2, 264	45.38	<.001	.256
Training Group*	1, 132	7.08	.009	.051
Experiment*	1, 132	8.05	.005	.057
Study Condition x Group*	2, 264	27.68	<.001	.173
Study Condition x Experiment	2, 264	2.04	.133	.015
Study Condition x Group x Experiment	2, 264	1.80	.167	.013

Statistically significant effects are marked by an asterisk. df = degrees of freedom; F = F-statistic; p = p-value; η_p^2 = effect size

Of main interest was the condition x group interaction, which was significant ($p < 0.001$).

To characterize the interaction, we analyzed the effect of condition in each group (immediate, delayed) separately. The immediate group showed the same pattern as the immediate group in Roediger and Karpicke (2006a), with more study resulting in better recall ($SSS > SST > STT$, $F(2, 136) = 51.87$, $p < 0.001$, $\eta_p^2 = 0.43$, linear trend $F(1, 68) = 84.58$, $p < 0.001$, $\eta_p^2 = 0.55$). However, this pattern did not reverse in the delayed recall group. There were still reliable differences among conditions ($F(2, 132) = 18.66$, $p < 0.001$, $\eta_p^2 = 0.22$), but the pattern was quadratic rather than linear (linear trend $F(1, 66) = 0.001$, $p = 0.97$, $\eta_p^2 = 0.00$; quadratic trend $F(1, 66) = 41.04$, $p < 0.001$, $\eta_p^2 = 0.38$). Delayed recall was the highest in the SST condition that included repetition in addition to self-testing ($M_{\text{recall}} = 60\%$) rather than in the condition that maximized restudy (SSS) or maximized self-testing (STT), which both showed approximately 50% recall. The same quadratic pattern, and reliable delayed recall advantage for the SST condition, was observed in both Experiments (both quadratic trend $F > 16.9$, $p < 0.001$; see Figure 3).

The Effect of Restudy Before Test vs. After Test

Our secondary question was whether restudy after test (STS) provides additional benefits compared to a restudy before test (SST). Full results of the 2 x 2 x 2 repeated measures ANOVA, with study condition [SST, STS] as a within-subject factor, and group [immediate, delay] and experiment [Experiment 1, Experiment 2] as between-subject factors are reported in Table 2 and visualized in Figure 4. Of main interest was the effect of study condition and its interactions. The main effect of study condition was significant ($F(1, 132) = 6.19, p = 0.014, \eta_p^2 = 0.045$), as was the condition x group interaction ($F(1, 132) = 7.60, p = 0.007, \eta_p^2 = 0.054$). To follow up on the interaction, we evaluated the effect of test-timing condition (SST vs. STS) within each group. At immediate recall, we found a significant advantage of restudy after self-test, with 70% recall in the STS condition compared to 63% recall in the SST condition ($t(68) = 4.15, p < 0.001, d = 0.50$). However, contrary to our prediction, no advantage was found during delayed recall, with 60% recall success in both SST and STS conditions ($t(66) = 0.18, p = 0.86, d = 0.02$).

Figure 4. Mean cued recall during immediate (solid lines) and delayed (dashed lines) fill-in-the-blank recall test. Black lines represent data from Experiment 1 (delayed test after 2 days), gray lines represent data from Experiment 2 (delayed test after 7 days). Error bars denote standard error of the mean.

Table 2

Effect of Restudy Before and After Test, Repeated Measures ANOVA Results.
Condition (SST, STS) x Group (Immediate, Delay) x Experiment (Exp 1, Exp 2)

Effect	df	F	p	η_p^2
Study Condition*	1, 132	6.19	.014	.045
Training Group*	1, 132	6.28	.013	.045
Experiment*	1, 132	7.39	.007	.053
Study Condition x Group*	1, 132	7.60	.007	.054
Study Condition x Experiment	1, 132	0.32	.571	.002
Study Condition x Group x Experiment	1, 132	0.00	.997	.000

Statistically significant effects are marked by an asterisk. df = degrees of freedom; F = F-statistic; p = p-value; η_p^2 = effect size

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Discussion

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A classic study by Roediger and Karpicke (2006a) demonstrated a striking benefit of

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replacing study repetition with retrieval attempts. As would be expected, more study periods led

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to better recall on an immediate test. Yet, after a week delay, the pattern of results reversed and

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recall was highest in those who had only a single study period followed by multiple retrieval

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attempts, even though no feedback was ever provided on those retrieval attempts. As each study

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period was minutes long and contained repeated readings of the material within a single study

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period, here we asked whether the same pattern of results replicates when each study opportunity

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is more time limited. Using briefly presented academically relevant facts, the current results

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partially, but not fully, replicated retrieval benefits for delayed recall. Specifically, we did not

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find evidence that individuals were better off by replacing all study repetitions with retrieval

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attempts. Instead, our results showed that including a study repetition in addition to self-testing

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(SST) lead to the highest delayed recall, outperforming both all-study (SSS) and multi-test (STT)

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conditions. Our secondary question was whether having an opportunity to restudy after a test

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rather than before a test may lead to better learning and retention, as tests have been shown to

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enhance subsequent learning. The results were mixed in that regard. Participants indeed better

remembered items that were restudied after a test (STS) than items that were restudied before a test (SST), but only when tested immediately. Delayed recalled was equivalent across STS and SST conditions, indicating that the retrieval attempt per se provided a comparable benefit to memory, irrespective of timing.

Our results emphasizing the importance of repetition in addition to retrieval practice are intuitive, but contrast with the results of the seminal Roediger and Karpicke (2006a) study that inspired our task design. In Experiment 2 of Roediger and Karpicke (2006a), repetition lead to superior initial learning ($SSSS > SSST > STTT$ immediate recall), but the order of conditions flipped completely for delayed recall ($SSSS < SSST < STTT$ recall after a week delay). In our study, the benefit of retrieval practice on preventing forgetting was also observed, as evidenced by diminishing differences between immediate and delayed recall performance in conditions that included self-testing. However, the self-testing benefits did not outweigh the benefit of repetition. Why does repetition seem more important in our study? Notably, a single “S” in past studies rarely meant a single brief presentation; rather, additional study repetition was often included for all items. For example, in Roediger and Karpicke (2006a) participants in the single-study STTT condition studied prose passages for a fixed 5-minute period, which provided them with an average of 3.4 study repetitions before testing. In Karpicke and Roediger (2007) a single study block consisted of five study repetitions of each wordlist. Thus, our findings of the importance of repetition are not at odds with these seminal papers. Rather, our results make the well-known importance of repetition for long-term retention (Bromage & Mayer, 1986; Davis et al., 1972; Donaldson, 1981; Mayer, 1983; Webb, 2007) more explicit in the context of retrieval-practice effects. Balancing testing with repetition may be optimal for maximizing retention in the

current study because it combined the benefits of study repetition for learning and retrieval practice for retention.

A second goal of our study was to further our understanding of test-potentiated learning by comparing the relative benefits of restudy before retrieval practice versus restudy after retrieval practice (Arnold & McDermott, 2013; Izawa, 1966, 1970). Given prior work that showed retrieval attempts, even when unsuccessful, made subsequent study more productive (Kornell, 2014; Kornell et al., 2009), we hypothesized that restudy after test (STS) would boost learning and long-term retention to a greater degree than restudying material before testing (SST). Importantly, only the STS condition provided an opportunity for test-potentiated learning. Because no feedback was provided on retrieval attempts themselves, we avoided potentially conflating retrieval benefits with test-potentiated learning in all other conditions (Arnold & McDermott, 2013). For the immediate test, the results were consistent with our hypothesis (STS > SST). Self-testing may provide participants with the internal feedback that they have not yet mastered the material to the level necessary to support recall, thus helping to guide attention and make subsequent study more fruitful. Restudying after test may also confer benefits by increasing spacing between the two study opportunities, as past work has shown that spacing repetitions further apart results in better recall than when items are studied *en masse* (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Hintzman & Rogers, 1973; Kornell & Bjork, 2008; Melton, 1970). For example, in the current study, study repetitions in the SSS and SST conditions were separated by 3 blocks of intervening material while study repetitions in the STS condition was separated by 7 blocks of intervening material.

Curiously, the benefit of restudying after test rather than before test was no longer observed when the final test came on a later day, even though the benefit of a study after test

(Kornell, 2014) or the benefit of spacing study repetitions apart (Bahrick, Bahrick, Bahrick, & Bahrick, 1993; Cepeda, Vul, Rohrer, Wixted, & Pashler, 2008) has been observed even when a test is administered on a different day. Yet, here we observed equivalent long-term memory in the STS and SST conditions, and replicated this finding across two experiments with different delays. We speculate that while less was learned initially in the SST compared to STS condition, what was learned in the SST condition was easier to retain as all material was reinforced by test (see a detailed discussion in the bifurcation framework below). This is a novel observation that contrasts with prior work that manipulated study and test order and found better delayed memory for interleaved conditions (e.g., STST > SSTT in Karpicke & Roediger, 2007). As prior studies typically provided a final retrieval practice in both conditions, this additional opportunity to reinforce restudied items may have provided an additional boost to performance in the interleaved condition by combining the strength of test-potentiated learning effects and retrieval practice effects (Arnold & McDermott, 2013). Without the additional retrieval practice opportunity, we isolated test-potentiated learning effects from retrieval practice effects to a greater degree than prior work, finding that restudy after test and restudy before test may be equally beneficial for long-term retention (delayed STS = SST).

The mechanisms through which retrieval practice impacts long-term memory retention are still a matter of debate. One possibility is that retrieval practice provides additional pathways through which to reactivate knowledge (Anderson, 1983; Collins & Loftus, 1975). According to this viewpoint, repetition serves to reactivate the same memory exactly as it was encoded and therefore strengthens the connections from the originally encoded pathway for retrieval. But testing, especially cued- or free-recall, may activate other related concepts and provide additional pathways through which one can retrieve the same information (Carpenter, 2009, 2011; Pyc &

Rawson, 2010). Our finding of maximal long-term retention in the STS and SST conditions (with no difference between them) is consistent with this perspective as participants had the opportunity to *both* strengthen the original pathway through repetition *and* create a new pathway through cued-recall testing in both conditions. A recent study by Zheng et al. (2016) further supported the idea of multiple pathways by demonstrating that the benefit of testing can be pushed even further, and memory retention increased, when testing involves practicing multiple retrieval routes as opposed to just one. While a balance between study and testing led to the best long-term memory retention outcome in the current paradigm, it may be interesting to probe in future studies whether a condition with multiple tests could become superior if each test had a different format, potentially providing more pathways to the same information.

The benefits of testing are typically viewed in terms of protection against forgetting that is qualitatively different from repetition alone (Nungester & Duchastel, 1982; Roediger & Karpicke, 2006b; Roediger & Butler, 2011). This view is consistent with neuroscience of memory consolidation that has shown distinct neural substrates for consolidated memories that make them stable and resistant to forgetting (Huang, 1998). Furthermore, retrieval elicited by testing can trigger rapid consolidation resulting in memory stabilization (Antony, Ferreira, Norman, & Wimber, 2017; see also Keresztes, Kaiser, Kovcs, & Racsmny, 2014; Wing, Marsh, & Cabeza, 2013). However, Kornell and colleagues (2011) noted that one does not need to postulate qualitative memory differences and distinct forgetting rates between repeated versus tested items. Instead, they propose that memory strength of all items may be falling at a constant rate and the apparent lack of forgetting after retrieval results from a *bifurcation* – or split – of the distribution of memory strength values in response to retrieval. A retrieval attempt (or testing without feedback) strengthens a subset of items that are above threshold and can be recalled at

the moment but does not strengthen items that are below threshold and thus not recalled. This results in a distribution of memory strengths that is bifurcated, with a subset that is below threshold and another that is high above threshold. Restudy, on the other hand, strengthens all items but less so than testing. Thus, even if memory strength for both restudied items and tested items falls at the same rate, it takes the retrieval-boosted items much longer to reach the threshold below which they are no longer retrievable, leading to an apparent lack of forgetting. We suspect that retrieval practice results in an actual reduction in forgetting thanks to structural changes in the neural substrate (Huang, 1998). Nevertheless, either framing of retrieval effects – decreased forgetting rates or selective disproportionate increases of memory strength – are equally applicable to the current behavioral data.

Finally, the current findings of STS advantage over SST at immediate test but not after a delay inform current models of testing effects and support the notion that restudy after a test yields greater benefits than restudy before a test (Kornell, 2014). For example, using the bifurcation model framework (Kornell et al., 2011), let us consider what would be predicted in each condition if one assumes (a) a single study parameter or (b) a higher study parameter for restudy after test. As schematically illustrated in Figure 5, assuming a single study parameter that is equivalent between SST condition (first row) and STS condition (second row) does not predict our current data well. Whether the distribution of memory strengths first shifts right and then is bifurcated at threshold in the SST condition, or is first bifurcated and then shifts right in the STS condition, the same number of items remain below threshold immediately after learning, and similar performance would be expected at immediate test. After a delay, one would expect a greater benefit for the SST condition because more items are in the stronger, bifurcated part of the distribution and thus less likely to reach forgetting threshold as memory strength for all items

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Figure 5. Conceptual illustration of the current SST vs. STS findings within the bifurcation model framework. The bell curves in the first column illustrate the presumed distribution of memory strength across items after initial study. Arrow illustrates the retrieval threshold, such that items above threshold would be recalled if tested at that time while items below threshold would not be recalled. Threshold can be anywhere along the x-axis (depending on the material, study or test format) but is placed at approximate middle here for simplicity and to approximate the observed immediate recall of items studied just once (near 50%). Bifurcation framework proposes that restudy evenly increases memory strength for all items (shifts the distribution right; second column of the first row) while testing only increases memory strength for items above threshold, but more so than study (distribution bifurcates at threshold; second column of the second row). This yields distinct predicted distributions of memory strengths for the SST (first row) vs. STS conditions (second and third row), as the distributions are bifurcated at different points. Immediate recall. The third column illustrates the presumed distributions in these conditions immediately after learning; immediate recall performance would correspond to the proportion of items above threshold at that time. Assuming a fixed study parameter in the STS condition equal to the SST condition yields predictions that do not match current data well because the predicted immediate recall is the same in both conditions (row 2). Assuming a greater study-related memory strength increase when study follows a test in the STS condition (larger shift right) yields predictions aligning with current results (row 3). Delayed recall. Time delay is assumed in the bifurcation framework to lead to a relatively uniform decrease of memory strength for all items (distribution shifting left; fourth column). Delayed recall performance would correspond to the proportion of items above threshold at that time. Because more items end up in the upper (stronger, bifurcated) portion of the distribution in the SST condition than STS condition, delayed recall would be expected to be greater in the SST (row 1) than STS (row 2) condition, unless STS condition has an initial advantage (row 3). Under some circumstances, such as if delay/forgetting is large and some items from the upper bifurcated distribution of the SST condition fall below threshold, it may be possible to account for the equivalent delayed SST=STS finding even without assuming a restudy after test advantage (row 1 and row 2 of column 5).

decreases over time. Neither of these predictions matches the current data. In contrast, assuming that study-related increase in memory strength is greater when restudy follows testing in the STS condition, one would expect immediate recall benefit for the STS condition, with fewer items below threshold (Figure 5, third row). After a delay, relatively equal performance can be also accounted for: fewer items would reach forgetting threshold in the SST condition than in the STS condition because SST condition yields more items in the stronger portion of the bifurcated distribution. Thus, assuming a larger shift in memory strength for restudy after test better accounts for the current data than assuming a fixed study benefit. As a side note, while we found about equal delayed performance after both a 2-day delay and 7-day delay, one may expect from the bifurcation framework that the relative benefit of either condition after a delay may depend on the length of the delay, given that the distributions are bifurcated at different points. Future studies may test this prediction by using a greater range of delays.

Conclusions

Understanding how testing should be balanced with opportunities to restudy material is important for determining optimal learning strategies that can be implemented in personal study and inform educational approaches. Here, we found that when study opportunities are limited to a single brief presentation, akin to briefly encountering information in an academic lecture or textbook, balancing self-testing with repetition may provide the maximal benefit. Restudying after a retrieval attempt provided an additional benefit compared to restudying before a retrieval attempt on an immediate test, but this benefit did not carry over a delay. These results inform existing cognitive theories of testing effects, provide new insights into the conditions that promote encoding and long-term retention, and have practical implications for education.

473 Open Practices

474 None of the experiments discussed in the current report were preregistered. Data and
475 stimuli are freely available in the *Retrieval practice and restudy in long-term memory for briefly*
476 *encountered facts* repository on the Open Science Framework
477 (https://osf.io/3fkup/?view_only=355d5837829445f4830ba93df45a47b2). The repository is
478 currently private but will be made publicly available upon acceptance for publication. A formal
479 power analysis with an effect size estimate unique to the current study was not performed.
480 Rather, we used a target sample size that we previously determined to be sufficient for detecting
481 medium-sized effects.

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