



Relearning can eliminate the effect of retrieval-induced forgetting

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Abstract

The retrieval of a subset of items can cause the forgetting of other, non-retrieved items, a phenomenon known as retrieval-induced forgetting. Initial work suggested that giving people the opportunity to restudy non-retrieved items following retrieval practice is sufficient to eliminate the effect of retrieval-induced forgetting, but more recent work has suggested otherwise. If retrieval-induced forgetting is not eliminated by restudy, then such a finding would have important implications for understanding the theoretical nature of retrieval-induced forgetting. It would suggest, for example, that retrieval-induced forgetting reflects more than the temporary reduction in the accessibility of non-retrieved items in memory. The two experiments reported here sought to clarify this issue, with the results suggesting that retrieval-induced forgetting can be eliminated by restudy. Indeed, retrieval-induced forgetting was eliminated by restudy even when the forgetting effect was produced by three rounds of retrieval practice instead of one round of retrieval practice. These findings are consistent with the idea that retrieval-induced forgetting, at least under the conditions of the current experiments, reflects a temporary reduction in the accessibility of non-retrieved items in memory.

Introduction

Retrieval does not simply make information accessible. As argued by Bjork (1975; p. 124), there is a kind of Heisenberg principle in memory, such that “... an item can seldom, if ever, be retrieved from memory without modifying the representation of that item in memory in significant ways.” The consequences of retrieval are multifarious, and they often promote the future accessibility of the information that is retrieved (Roediger & Karpicke, 2006), but retrieval can also come at a cost. Research has shown, for example, that retrieving some items can cause the forgetting of other items, a phenomenon known as retrieval-induced forgetting (Anderson, Bjork, & Bjork, 1994; Bäuml, 2002; Blaxton & Neely, 1983; Roediger, 1978).

Retrieval-induced forgetting has been studied in many ways, but most typically using a retrieval-practice paradigm in which participants study a list of category–exemplar pairs (e.g., fruit—lemon, drinks—gin, fruit—banana,

drinks—whiskey), and then repeatedly retrieve half of the exemplars from half of the categories (e.g., fruit—le___). The consequences of this selective retrieval practice are then observed at the final test. Compared to items from categories that did not receive retrieval practice (Nrp items; *gin, whiskey*), practiced items from practiced categories (Rp+ items; *lemon*) become more accessible, whereas non-practiced items from practiced categories (Rp- items; *banana*) become less accessible. This impairment in the ability to remember Rp- items relative to Nrp items is referred to as retrieval-induced forgetting.

By employing numerous variations of the retrieval-practice paradigm, researchers have shown retrieval-induced forgetting to be a highly robust and general phenomenon (for a quantitative review, see Murayama et al., 2014; for a qualitative review, see Storm et al., 2015). Indeed, it has been observed in just about every context in which it has been studied.

According to the inhibition account of retrieval-induced forgetting (Anderson, 2003; Storm & Levy, 2012), cues presented during retrieval practice activate both target items and non-target items (Rp+ and Rp- items, respectively). “Fruit-le,” for example, might activate the target item, “lemon,” as well as the non-target item, “banana.” Inhibition is presumed to suppress activation of non-target items, thus counteracting competition for retrieval, and facilitating access to the target

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item while impairing access to non-target items. According to this account, the impaired recall of Rp– items relative to Nrp items reflects the persisting aftereffect of a goal-directed inhibitory process that takes place during retrieval practice.

Over 25 years of research has produced substantial support for the inhibition account of retrieval-induced forgetting (Anderson, 2003; Bäuml & Kliegl, 2017; Murayama et al., 2014; Storm & Levy, 2012). It is important to note, however, that retrieval-induced forgetting can also be caused by other mechanisms. Retrieval practice, for example, can cause retrieval-induced forgetting by strengthening Rp+ items in a way that leads them to block or otherwise interfere with the recall of Rp– items at the final test (e.g., Jonker et al., 2013; Raaijmakers & Jakab, 2013; Verde, 2012). According to such accounts, forgetting is not the consequence of a goal-directed mechanism that takes place during retrieval practice. Rather, it is a side effect of the strengthening of practiced items or changes in context caused by retrieval practice. Most researchers take the view that multiple mechanisms underlie retrieval-induced forgetting, and that the role of any specific mechanism (e.g., inhibition, interference) is likely to vary as a function of the nature of the paradigm employed (e.g., whether interference effects are controlled at the time of the final test).

An important theoretical question that remains largely unanswered is whether retrieval-induced forgetting reflects a temporary reduction in the accessibility of information in memory or the consequences of changes in memory that are more substantial and long-lasting. In the study of memory, retrieval strength must be distinguished from storage strength (Bjork & Bjork, 1992). Retrieval strength refers to an item's accessibility, an index which can be observed directly; storage strength, on the other hand, refers to how well learned or entrenched an item is with other items in memory, an index that must be inferred (for similar distinctions, see Estes, 1955; Hull, 1943; Tulving & Pearlstone, 1966). Although retrieval strength and storage strength are often correlated, they are not always. In some instances, an item with high storage strength can be difficult to retrieve, such as when someone experiences a tip-of-the-tongue state for information they know well. In other instances, an item with low storage strength can be easy to retrieve, such as when some new piece of information is just learned. Moreover, as argued by the New Theory of Disuse (Bjork & Bjork, 1992), an item's storage strength is assumed to have a powerful impact on changes in retrieval strength, such as in determining how quickly an item is forgotten over time, or how rapidly it can be relearned.

Whether discussed explicitly or implicitly, retrieval-induced forgetting has been generally assumed by most researchers to reflect a reduction in retrieval strength, not storage strength. In other words, Rp– items are assumed to be forgotten not because they have become less well stored

or damaged in some permanent sense, but because they are rendered temporarily less accessible. Said differently, Rp– items are assumed to lose retrieval strength while maintaining their storage strength. This assumption about the nature of inhibition can be traced as far back as Brunton's (1883) classic definition of inhibition as the "arrest of the function of a structure or organ, by action upon it of another, while the power to execute those functions is still retained, and can be manifested as soon as the restraining power is lifted" (for related discussion, see Bjork, 2007; MacLeod, 2007).

If inhibition causes a temporary reduction in retrieval strength, then one might assume that retrieval-induced forgetting would be relatively short-lived. Indeed, as argued by MacLeod and Macrae (2001, p. 149): "...inhibitory effects need endure only until perceivers have satisfied their current processing objective ... if inhibition were to last indefinitely, its effects would be equivalent to the permanent erasure of items in memory." This characterization suggests that inhibition should last just minutes, or even seconds—that once competition is resolved, and a retrieval attempt is completed, the restraining influences of inhibition would be absolved as well. To the contrary, however, retrieval-induced forgetting has been shown to be remarkably persistent. Most studies have employed delays of 5–20 min, delays which would seem sufficient for the consequences of inhibition to abate. Although there is some evidence that retrieval-induced forgetting is eliminated following a 24-h delay (e.g., MacLeod & Macrae, 2001), more recent work has shown that retrieval-induced forgetting can persist for days or even weeks following retrieval practice (Murayama et al., 2014; Storm, Bjork, & Bjork, 2012).

Another way that researchers have sought to investigate the nature and durability of retrieval-induced forgetting is by manipulating whether items are re-exposed to participants prior to the final test. If Rp– items are inhibited during retrieval practice, and if that inhibition reflects a temporary form of deactivation (e.g., a reduction in retrieval strength, not a reduction in storage strength), then it stands to reason that the restudy of those items would reverse the deactivation and eliminate the effect of retrieval-induced forgetting. To examine this possibility, Storm, Bjork, and Bjork (2008) employed a variant of the retrieval-practice paradigm in which participants restudied half of the studied items (Rp– items and Nrp items) following retrieval practice. When items were not restudied, the typical effect of retrieval-induced forgetting was observed. When items were restudied, the effect of retrieval-induced forgetting was eliminated (for related findings, see Hulbert & Norman, 2015; Storm et al., 2012). Indeed, although it did not reach statistical significance, the retrieval-induced forgetting effect was found to be numerically reversed following restudy, with

Rp– items becoming numerically more recallable than Nrp items.

Interestingly, the reversal of retrieval-induced forgetting into retrieval-induced facilitation following restudy is predicted by the New Theory of Disuse (Bjork & Bjork, 1992). According to the New Theory of Disuse, the benefits of restudy for producing changes in new learning depend on existing levels of retrieval strength and storage strength. Specifically, whereas storage strength is assumed to potentiate new learning, retrieval strength is assumed to impede new learning. Thus, if retrieval practice causes Rp– items to have lower retrieval strength, while not affecting their underlying storage strength (relative to Nrp items), then Rp– items should benefit more from restudy than Nrp items, and possibly to an extent that leads them to become more recallable than Nrp items. Given the non-significant facilitation effect reported by Storm et al. (2008), however, the reliability of this reversal effect remains unknown.

Indeed, recent work has not only questioned the reversal effect (that Rp– items become more recallable than Nrp items following restudy), but the core finding that Rp– items benefit more from restudy than Nrp items. As part of the Open Science Framework's Reproducibility Project (Open Science Collaboration, 2015), an independent investigator—using the same materials and procedures as those of Storm et al. (2008)—failed to replicate the original results (Callahan, 2015). Specifically, Callahan found that retrieval-induced forgetting persisted after restudy, with Rp– items benefiting from restudy to the same extent as Nrp items. As a result, the retrieval-induced forgetting effect observed following restudy was of the same magnitude as the retrieval-induced forgetting effect observed without restudy. This failure to replicate the Storm et al. (2008) findings was surprising, especially given the large sample sizes used in the two experiments. If Callahan's results are reliable, however, and if restudy does not eliminate (or even significantly reduce) retrieval-induced forgetting, then such a finding would have important practical and theoretical implications.

From a theoretical standpoint, such a finding would provide new insight into the mechanisms underlying retrieval-induced forgetting. It would contradict, for example, the general assumption that retrieval-induced forgetting reflects a temporary reduction or deactivation in the accessibility of items in memory. Indeed, such a finding would be more consistent with the idea that retrieval-induced forgetting reflects an enduring reduction in the accessibility of non-practiced items in memory (or even a reduction in storage strength), with retrieval acting to modify memory in a much more substantial or meaningful way than has been previously appreciated.

Long-lasting or even permanent effects of retrieval-induced forgetting could provide certain functional advantages. In addition to resolving competition during retrieval

practice, forgetting non-target items may prevent competition in the future. From a statistics-of-use point of view (Anderson & Milson, 1989), for example, items inappropriate for retrieval at one point in time are unlikely to be appropriate for retrieval at another point in time, especially when the cues or context at the two points are similar. An effective means of resolving competition, therefore, may be to not only overcome interference when it occurs but to modify the system to prevent it from occurring in the future (Kim, Lewis-Peacock, Norman, Turk-Browne, 2014). Moreover, by affecting storage strength, retrieval may act to update and reshape the contents of memory in a goal-driven and self-oriented way that prepares people for the cues and contexts that are likely to follow (Conway & Pleydell-Pearce, 2000). In this way, retrieval-induced forgetting may not be an *aftereffect* of an adaptive mechanism in the functioning of memory as much as it is an adaptive mechanism in the functioning of memory.

There are good reasons to be skeptical of the idea that differences in retrieval strength reflect differences in storage strength (Soderstrom & Bjork, 2015). In the context of retrieval-induced forgetting, however, the possibility warrants consideration. Existing knowledge and experience shapes and facilitates new learning (Bartlett, 1932; Bransford & Johnson, 1972; Schacter, 2001), and it may do so partly because it is co-opted in the consolidation of new learning. A downside of having old learning facilitate new learning, however, may be that old learning is put at risk of being lost or altered by new learning (Loftus & Loftus, 1980). New learning must also be instantiated through consolidation (McGaugh, 2015; Müller & Pilzecker, 1900; Wixted, 2004), a process which may be impacted by retrieval in ways not impacted by other types of learning. Indeed, the idea that retrieval sets the stage for the modification of existing memory traces has been the direct focus of research on reconsolidation, which has shown that re-activated memories can be susceptible to significant disruption (e.g., Chan & LaPaglia, 2013; Hupback et al., 2013; Nader & Hardt, 2009; Shiller et al., 2010).

A discussion of the precise mechanisms by which retrieval might cause retrieval-induced forgetting via reconsolidation is beyond the scope of the present paper. The need to consider such a possibility, however, would be enhanced significantly if the results observed by Callanan (2015) are proven reliable. That is, if retrieval-induced forgetting persists not only following long delays, but following restudy, then such a pattern of results would pose serious problems for the assumption that retrieval-induced forgetting reflects a temporary reduction in retrieval strength—instead, it would suggest that retrieval-induced forgetting reflects a more permanent change in storage strength. Moreover, such a finding would have important practical implications. It would suggest that the forgetting observed in many applied situations

(e.g., learning, eyewitness memory, social cognition, autobiographical memory, creative cognition) would be likely to persist even after forgotten items are re-encountered. In an eyewitness context, for example, re-exposure to a forgotten detail of a crime would not be expected to lead to the full recovery of that detail in memory.

Experiment 1

The primary goal of the present study was to provide a more definitive answer to the question of whether restudy reduces and or eliminates the effect of retrieval-induced forgetting. In prior work, Storm et al. (2008) found that restudy not only reduced the effect of retrieval-induced forgetting, but eliminated it completely, leading to a numerical effect of retrieval-induced facilitation. In contrast, Callahan (2015) failed to find any evidence of a reduction in retrieval-induced forgetting, with similar levels of forgetting observed regardless of whether items were restudied prior to final test. Given the stark contrast in the results of these two studies, we sought to replicate, as closely as possible, the methods used by Storm et al. and Callahan.

If retrieval-induced forgetting is eliminated by restudy, then such a finding would be consistent with the inhibition account's assumption that retrieval-induced forgetting reflects a temporary deactivation in the retrieval strength of Rp– items relative to Nrp items. If retrieval-induced forgetting persists following restudy, however, then such a finding would suggest a need to reconsider what it means for an item to be inhibited, and perhaps the mechanisms by which retrieval-induced forgetting occurs more generally.

Method

Participants

A total of 580 undergraduate students at the University of California, Santa Cruz (M age = 19.9), participated for partial course credit in a psychology class. The sample was determined based on several considerations. First, we wanted the total number of participants to be at least as large as the combined total in the relevant conditions of Storm et al. (2008) and Callahan (2015), thus requiring at least 462 participants. Second, we sought to have enough power to determine the statistical significance of a relatively small effect of retrieval-induced forgetting. In the conditions that did not involve a final round of restudy before final test, the 230 participants in the studies by Storm et al. (2008) and Callahan (2015) exhibited an average raw effect size of retrieval-induced forgetting of 0.0336 ($SD = 0.1951$). This analysis suggested that to have 80% power, 534 participants

would be needed in the study overall. Ultimately, we decided to run 576 participants, requiring 36 participants in each of the 16 counterbalancing conditions. Four additional participants were run accidentally after data collection was complete. We chose to include these participants in the analysis, but the same pattern of results was observed with them excluded. We took the conservative approach of not excluding any participant or any data point for any reason. It should be noted, however, that we were unable to include data from five additional participants who, for various reasons, were either not given the initial learning phase (1 participant), received retrieval practice for all categories instead of half of the categories (1 participant), or did not complete the final test (3 participants).

Design

Participants were randomly assigned to one of the four between-subject conditions shown schematically in Fig. 1: (1) one block of retrieval practice; (2) one block of retrieval practice, and then one block of restudy; (3) one block of retrieval practice, one block of restudy, and then a second block of retrieval practice; (4) one block of retrieval practice, one block of restudy, a second block of retrieval practice, and then a second block of restudy. Consistent with Callahan (2015), we did not include the fifth condition employed by Storm et al. (2008) in which participants received a final block of retrieval practice, as that condition was not necessary for examining the effect of restudy on retrieval-induced forgetting.

Participants studied 48 category–exemplar pairs before experiencing the blocks of retrieval practice and restudy described above. Both retrieval practice status and restudy were manipulated within-subjects. For participants in the first between-subject condition, 24 of the studied exemplars served as Rp– items, and the other 24 served as Nrp items. For participants in the other three between-subject conditions, 12 of the exemplars served as Rp– items that were

Group 1				Study	Rp	Test
Group 2			Study	Rp	Restudy	Test
Group 3		Study	Rp	Restudy	Rp	Test
Group 4	Study	Rp	Restudy	Rp	Restudy	Test

Fig. 1 Schematic illustrating the four between-subject retrieval-practice/restudy conditions. Participants in each condition were tested 5 min after finishing the final block of either retrieval practice or restudy, depending on the condition

restudied, 12 served as Rp– items that were not restudied, 12 served as Nrp items that were restudied, and 12 served as Nrp items that were not restudied. This design allowed us to measure retrieval-induced forgetting as a function of the number of rounds of retrieval practice, and as a function of whether the items were restudied following retrieval practice.

Materials

We used the same 48 category–exemplar pairs employed by Storm et al. (2008) and Callahan (2015). The pairs consisted of six exemplars from each of eight categories. The exemplars were of moderately high taxonomic frequency, and no two exemplars within a category started with the same initial letter. For counterbalancing purposes, the eight categories were divided into two sets of four. Half of the participants received retrieval practice for one set of categories, whereas the other half received retrieval practice for the other set of categories. The two sets were further divided into two subsets such that half of the categories that received retrieval practice would be restudied, and half of the categories that did not receive retrieval practice would be restudied. Counterbalancing across participants ensured that every studied item served equally often in each of the retrieval-practice/restudy conditions.

We employed an extra-list form of retrieval practice in which participants generated non-studied exemplars from each of the practiced categories. This type of practice was employed by Storm et al. (2008) and Callahan (2015), and it has been used in a variety of studies on retrieval-induced forgetting. Six extra-list retrieval-practice cues were created for each of the eight categories, with each cue consisting of the category name along with the two-letter stem corresponding to an exemplar of relatively low taxonomic frequency. None of the extra-list exemplars started with the same initial letter as any of the studied exemplars from the same category. One of the benefits of using the extra-list retrieval practice design (as opposed to a within-list design) is that it allows all studied items to serve as Rp– items and Nrp items, thus increasing the number of observations per participant. Moreover, as shown in the meta-analysis by Murayama et al. (2014), studies using extra-list retrieval practice designs exhibit retrieval-induced forgetting effects that are just as large as studies using within-list retrieval practice designs, and the same types of evidence supporting the inhibition account have been observed when using the two designs (e.g., strength independence, Bäuml, 2002; Storm et al., 2006; competition dependence, Storm, Bjork, & Bjork, 2007; individual differences, Storm & Angello, 2010; Storm & Jobe, 2012; for further discussion, see Murayama et al., 2014; Storm & Bui, 2016).

Procedure

The experiment was conducted in three phases: study, retrieval practice/restudy, and test. The procedure was identical to that employed by Storm et al. (2008) and Callahan (2015).

Study Participants were first exposed to each of the 48 category–exemplar pairs. The pairs were presented in random order on a computer screen at a rate of one pair per second, with the only constraint that no two consecutive pairs came from the same category.

Retrieval practice/restudy Participants were randomly assigned to one of the four retrieval-practice/restudy conditions displayed in Fig. 1. Each block of retrieval practice consisted of participants attempting to generate 24 extra-list exemplars from the associated category-plus-two-letter-stem cues (six from each of the four practiced categories). The cues appeared for 5 s each, and participants were instructed to write down the exemplar that completed each stem. Each block of restudy consisted of participants being re-presented 24 of the category–exemplar pairs that were initially studied. More specifically, all six exemplars from two of the practiced categories and two of the non-practiced categories were restudied. As in the initial study phase, the pairs were presented for 1 s each.

Test The final test was administered after a 5-min delay. The test consisted of 48 category-plus-one-letter-stem retrieval cues (tool: w____) presented for 3 s each, with participants instructed to recall the exemplars that had been studied during the initial study phase. They were never tested on the items that were generated during retrieval practice. Participants responded out loud for the experimenter to record. The data can be found on the Open Science Framework at <https://osf.io/dp8cu/files/>.

Results

Retrieval practice performance

Retrieval practice performance was in line with that observed by Storm et al. (2008). Specifically, participants generated exemplars on 35% (SE = 1%) and 40% (SE = 1%) of the trials in the first and second blocks of retrieval practice, respectively.

Final test performance

Recall performance on the final cued-recall test for exemplars exposed during the study phase as a function of restudy condition and retrieval-practice status are presented for each of the four groups of participants on the bottom panel of Fig. 2. For purposes of comparison, the results of Storm

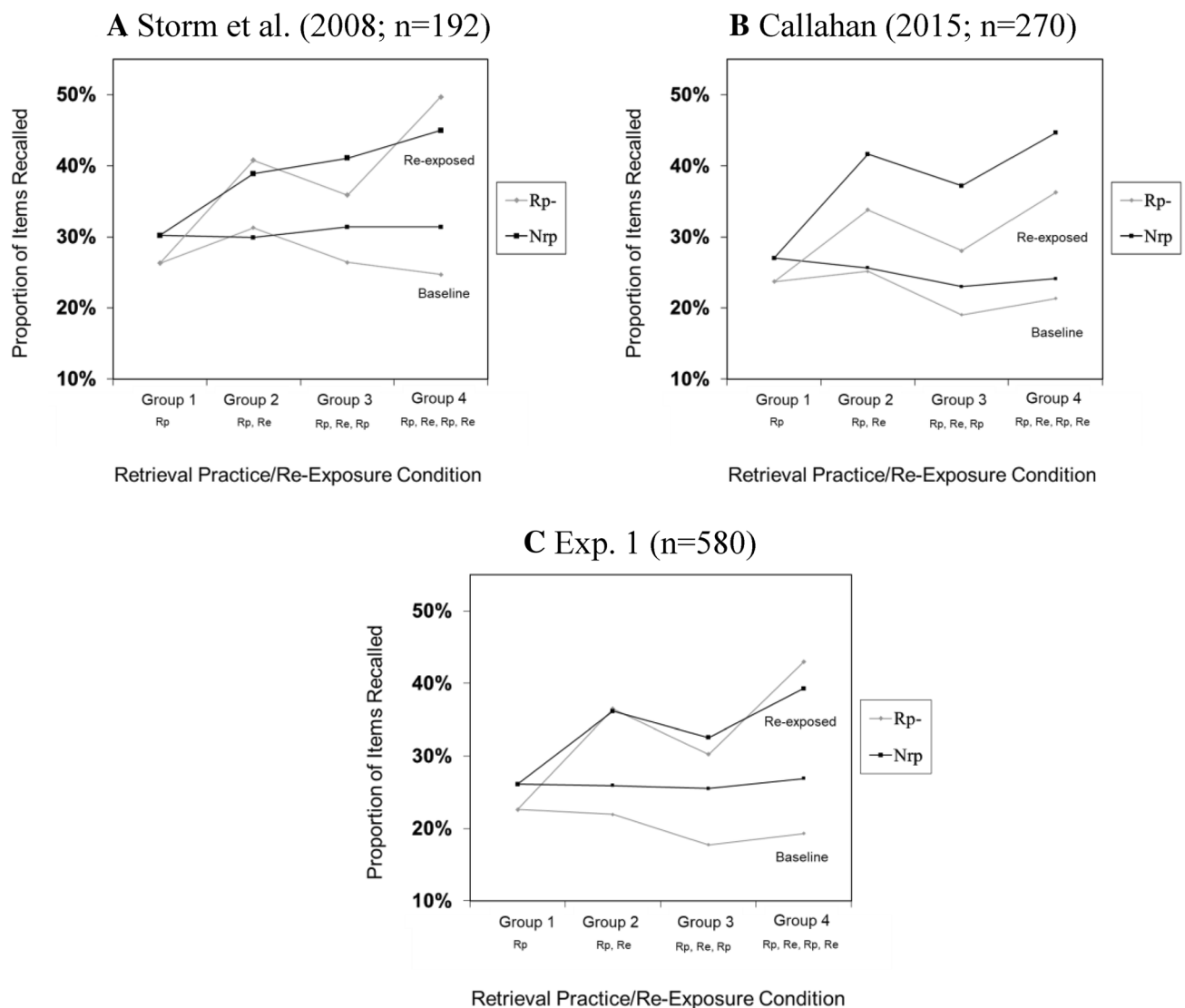


Fig. 2 The mean proportion of items recalled during the final test as a function experimental condition, item type (Rp– vs. Nrp), and whether such items were or were not restudied. **A** and **B** show the

results from Storm et al. (2008) and Callahan (2015), respectively. **C** shows the results from Experiment 1 of the current study

et al. (2008) and Callahan (2015) are reproduced in the top left and top right panels, respectively. As can be seen upon visual inspection, there were some minor deviations, but the results of the current study largely mirrored those of Storm et al., while standing in stark contrast to those of Callahan.

We analyzed the data first by conducting a 2 (restudy condition: restudied vs. not restudied) $\times$ 2 (retrieval-practice status: Rp– vs. Nrp) $\times$ 4 (retrieval-practice/restudy group: 1 vs. 2 vs. 3 vs. 4) mixed-design ANOVA, with retrieval-practice/restudy group serving as the only between-subjects variable. For the purposes of conducting the ANOVA, half of the categories for participants in group 1 were placed in the restudied condition, and the other half were placed in the not restudied condition, even though none of the categories were

restudied. Counterbalancing across participants ensured that all categories served equally often in these two arbitrary conditions. As can be seen in Table 1, the two-way interaction between retrieval-practice status and restudy condition was statistically significant, as was the three-way interaction. We next conducted more focused analyses to address the specific questions under investigation.

Retrieval-induced forgetting for non-restudied items
Recall for all non-restudied categories in all four groups was subjected to a 2 (Rp– vs. Nrp) $\times$ 2 (one block of retrieval practice vs. two blocks of retrieval practice) mixed-design ANOVA, with the number of retrieval-practice blocks serving as a between-subjects variable. Items in Conditions 2–4 that were restudied at any point in the experiment for a given

Table 1 Analysis of variance for final cued-recall performance

Source	<i>F</i>	<i>df</i>	η^2
Restudy	284.47***	1, 576	.331
RP status	29.74***	1, 576	.049
Group	17.78***	3, 576	.085
Restudy X RP status	20.30***	1, 576	.034
Restudy X group	53.77***	3, 576	.219
RP Status X group	1.82	3, 576	.009
Restudy X RP status X group	6.14***	3, 576	.031

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$

participant were not included in this analysis. Overall, a significant effect of retrieval-induced forgetting was observed, with significantly fewer Rp– items ($M = 0.204$, $SE = 0.005$) being recalled than Nrp items ($M = 0.261$, $SE = 0.006$), $F(1, 578) = 63.92$, $MSE = 0.015$, $p < 0.001$, $\eta^2 = 0.10$. Moreover, a significant interaction was observed such that the effect of retrieval-induced forgetting was greater following two blocks of retrieval practice (Rp– items: $M = 0.185$, $SE = 0.008$; Nrp items: $M = 0.262$, $SE = 0.009$; $t(290) = 7.02$, $p < 0.001$, $d = 0.411$, 95% CI [0.056, 0.099]) than it was following one block of retrieval practice (Rp– items: $M = 0.223$, $SE = 0.008$; Nrp items: $M = 0.261$, $SE = 0.009$; $t(288) = 4.08$, $p < 0.001$, $d = 0.240$, 95% CI [0.019, 0.055]), $F(1, 578) = 7.79$, $MSE = 0.015$, $p = 0.005$, $\eta^2 = 0.013$. This result is consistent with previous evidence that the magnitude of the retrieval-induced forgetting effect is affected by the amount of retrieval practice participants receive (e.g., Storm et al., 2008; but see Macrae & MacLeod, 1999).

The Effect of restudy on retrieval-induced forgetting As in the study by Storm et al. (2008), we assessed the effect of restudy on retrieval-induced forgetting by comparing the recall performance for Rp– and Nrp items in Conditions 1 and 3 (where the test took place without subsequent restudy) with the recall performance for Rp– and Nrp items in Conditions 2 and 4 (where the test took place after subsequent restudy). Items in Conditions 2, 3, and 4 that were never restudied were not included in this analysis. A 2 (retrieval practice status: Rp– vs. Nrp) $\times$ 2 (restudy condition: after restudy vs. not after restudy) mixed design ANOVA was conducted, with the latter factor serving as a between-subjects variable. Overall, a significant main effect of restudy was observed such that items were more recallable after restudy ($M = 0.387$, $SE = 0.007$) than they were not after restudy ($M = 0.279$, $SE = 0.008$), $F(1, 578) = 101.17$, $MSE = 0.033$, $p < 0.001$, $\eta^2 = 0.149$. More importantly, replicating the results of Storm et al. (2008), an interaction was observed such that Rp– items benefited significantly more from restudy than did Nrp items, $F(1, 578) = 10.61$, $MSE = 0.017$, $p = 0.001$, $\eta^2 = 0.018$. Specifically, whereas Nrp items were recalled at rates of 0.294 and 0.377 ($SEs = 0.009$) before and

after restudy, respectively, Rp– items were recalled at rates of 0.265 and 0.397 ($SEs = 0.009$) before and after restudy, respectively.

Additional t tests were conducted to assess the magnitude of the retrieval-induced forgetting effects both after, and not after, restudy. In the not-after-restudy conditions (Groups 1 and 3), a significant retrieval-induced forgetting effect was observed (Rp– items: $M = 0.265$, $SE = 0.008$; Nrp items: $M = 0.294$, $SE = 0.009$; $t(288) = 3.26$, $p = 0.001$, $d = 0.192$, 95% CI [0.012, 0.047]). In contrast, in the after-restudy conditions (Groups 2 and 4), a non-significant retrieval-induced facilitation effect was observed (Rp– items: $M = 0.398$, $SE = 0.010$; Nrp items: $M = 0.377$, $SE = 0.010$; $t(290) = -1.66$, $p = 0.098$, $d = 0.097$, 95% CI [-0.045, 0.004]). Consistent with the results of Storm et al. (2008), the size of the retrieval-induced facilitation effect was numerically larger for participants in Group 4 (Rp– items: $M = 0.430$, $SE = 0.014$; Nrp items: $M = 0.393$, $SE = 0.014$), $t(145) = 2.11$, $p = 0.04$, $d = 0.175$, 95% CI [-0.073, -0.002], than it was for participants in Group 2 (Rp– items: $M = 0.365$, $SE = 0.014$; Nrp items: $M = 0.362$, $SE = 0.014$), $t(144) = 0.184$, $p = 0.85$, $d = 0.015$, 95% CI [-0.036, 0.030].

The effect of restudy on retrieval-induced forgetting was also analyzed within-subjects by focusing only on participants in Conditions 2 and 4. A 2 (restudy condition: restudied vs. never restudied) $\times$ 2 (retrieval-practice status: Rp– vs. Nrp) $\times$ 2 (retrieval-practice/restudy group: 2 vs. 4) mixed-design ANOVA was run with group serving as the only between-subjects variable. Consistent with the results reported above, a significant interaction was observed between retrieval practice status and restudy condition such that the effect of retrieval-induced forgetting was greater for items that were never restudied (Rp– items: $M = 0.206$, $SE = 0.008$; Nrp items: $M = 0.264$, $SE = 0.009$), $t(290) = 5.22$, $p < 0.001$, $d = 0.306$, 95% CI [0.037, 0.081], than it was for items that were restudied (Rp– items: $M = 0.397$, $SE = 0.010$; Nrp items: $M = 0.377$, $SE = 0.010$), $t(290) = -1.59$, $p = 0.112$, $d = -0.094$, 95% CI [-0.044, 0.005], $F(1, 289) = 22.551$, $MSE = 0.020$, $p < 0.001$, $\eta^2 = 0.072$. Moreover, a three-way interaction was observed such that the two-way interaction was significantly greater in Condition 4 than it was in Condition 2, $F(1, 289) = 4.78$, $MSE = 0.020$, $p = 0.030$, $\eta^2 = 0.016$.

Finally, we conducted a Bayesian analysis (Wagenmakers, 2007) to quantify support for the hypothesis that restudy eliminated retrieval-induced forgetting. Specifically, we compared the fit of the data for items in the restudy conditions of Groups 2 and 4 under the null and alternative hypotheses, with the null hypothesis being the directional assumption that there is no effect of retrieval-induced forgetting. A Bayes Factor of 39.30 was observed favoring the null hypothesis, thus providing strong support for the conclusion that retrieval-induced forgetting was eliminated by restudy.

Experiment 2

The results of Experiment 1 replicated the results reported by Storm et al. (2008). Specifically, restudying Rp– and Nrp items following retrieval practice eliminated the effect of retrieval-induced forgetting. In “Experiment 2”, we sought to extend this finding focusing on the condition in which participants received retrieval practice followed by one round of restudy (Group 2). This condition alone is sufficient to test the main hypothesis that restudy can eliminate the effect of retrieval-induced forgetting.

A second goal of Experiment 2 was to test for a possible boundary condition on when restudy can eliminate retrieval-induced forgetting—specifically, by increasing the number of rounds of retrieval practice prior to restudy. In most experiments using the retrieval-practice paradigm, participants receive three rounds of retrieval practice, not the one round of retrieval practice employed in “Experiment 1”. Indeed, there is evidence that three rounds of retrieval practice can lead to a significantly larger effect of retrieval-induced forgetting than one round of retrieval practice (Murayama et al., 2014). Although restudy may be sufficient to eliminate retrieval-induced forgetting following a single round of retrieval practice, it is unclear whether it is sufficient to eliminate retrieval-induced forgetting following the more typical three rounds of retrieval practice. It is possible, for example, that the forgetting effect caused by multiple rounds of practice would be more durable than that caused by a single round of practice, and thus fail to be eliminated by restudy. To our knowledge, no prior studies have investigated whether the number of retrieval-practice trials can affect the likelihood of retrieval-induced forgetting persisting following restudy.

Method

The materials and procedure were identical to those employed in Group 2 of Experiment 1, except for one important difference. Specifically, participants received three rounds of retrieval practice instead of one round of retrieval practice. First, the participants studied 48 category–exemplar pairs. Second, they received three rounds of retrieval practice for new exemplars associated with half of the studied categories. The cues used in each round of

retrieval practice were the same but re-sorted in each round using a different random order. Third, participants restudied the exemplars associated with half of the categories (half of which were Rp– items, and half of which were Nrp items). This method resulted in four types of items: Restudied Rp– items, Restudied Nrp items, Non-Restudied Rp– items, and Non-Restudied Nrp items. Counterbalancing across participants ensured that all studied exemplars served equally often in each of the four conditions. Finally, after a 5-min delay, participants were given a final test for all 48 of the studied exemplars.

To determine the sample size, we ran a power analysis based on the data observed in “Experiment 1” and Storm et al. (2008). Specifically, assuming a raw effect size of 0.05 and $SD=0.1933$, we calculated that we would need 120 participants to have 80% power to observe a significant difference between restudied Rp– items and restudied Nrp items. By accident, we ran one additional participant, bringing the total sample to 121. As in “Experiment 1”, the participants were given partial credit in a psychology course for their participation, and no participants (or data points) were excluded from the analysis for any reason.

Results

Retrieval practice performance

Participants generated exemplars on 23% ($SE=0.01$) of the retrieval-practice trials.

Final test performance

Recall performance on the final cued-recall test for studied exemplars as a function of restudy condition and retrieval-practice status are displayed in Table 2 (along with, for comparison purposes, the data from Group 2 in Experiment 1). The data were analyzed using a 2 (restudy condition: restudied vs. non-restudied) $\times$ 2 (retrieval practice status: Rp– vs. Nrp) repeated measures ANOVA. Overall, a significant retrieval-induced forgetting effect was observed, with significantly fewer Rp– items ($M=0.257$, $SE=0.009$) recalled than Nrp items ($M=0.296$, $SE=0.009$), $F(1, 120)=15.61$, $MSE=0.012$, $p<0.001$, $\eta^2=0.12$. A significant effect of restudy was also observed, with restudied items ($M=0.336$, $SE=0.010$) being recalled significantly

Table 2 Proportion of exemplars recalled (and SEs of the mean) as a function of retrieval practice status and restudy status in Experiment 1 (Condition 2) and Experiment 2

Experiment	Not restudied		Restudied	
	Rp–	Nrp	Rp–	Nrp
Exp. 1: one round of RP	0.22 (0.01)	0.26 (0.01)	0.36 (0.01)	0.36 (0.01)
Exp. 2: three rounds of RP	0.18 (0.01)	0.25 (0.01)	0.33 (0.01)	0.34 (0.01)

better than non-restudied items ($M=0.217$, $SE=0.009$), $F(1, 120)=94.84$, $MSE=0.018$, $p<0.001$, $\eta p^2=0.44$. Most importantly, a significant interaction was observed such that the effect of retrieval-induced forgetting was greater in the non-restudied condition (Rp– items: $M=0.184$, $SE=0.011$; Nrp items: $M=0.250$, $SE=0.012$; $t(120)=4.29$, $p<0.001$, $d=0.390$, 95% CI [0.035, 0.096]) than it was in the restudied condition (Rp– items: $M=0.329$, $SE=0.013$; Nrp items: $M=0.343$, $SE=0.013$; $t(120)=0.89$, $p=0.374$, $d=0.081$, 95% CI [– 0.017, 0.044]), $F(1, 120)=5.09$, $MSE=0.016$, $p=0.026$, $\eta p^2=0.04$. Moreover, the results once again showed that Rp– items benefited significantly more from restudy than Nrp items. Whereas the recall of Nrp items increased by 0.093 following restudy, the recall of Rp– items increased by 0.145. These increases were remarkably similar to those observed in “Experiment 1” (0.102 and 0.145, respectively).

It is worth noting that although we failed to observe a significant effect of retrieval-induced forgetting following restudy, a small numerical effect was observed. To further quantify support for the hypothesis that restudy eliminated retrieval-induced forgetting, we used Bayesian analysis to compare the fit of the data for items in the restudy condition under the null and alternative hypotheses, with the null hypothesis being the directional assumption that there is no effect of retrieval-induced forgetting. A Bayes Factor of 4.15 was observed favoring the null, thus providing substantial support for the idea that retrieval-induced forgetting was eliminated by restudy.

General discussion

The current study examined whether re-exposure to studied items is sufficient to eliminate the effect of retrieval-induced forgetting. Initial work by Storm et al. (2008) suggested that retrieval-induced forgetting can be eliminated by restudy, whereas a well-powered replication attempt by Callahan (2015)—conducted as part of the Open Science Collaboration replication endeavor—suggested it is not. With 701 participants across two experiments, the results of the current study provide clear evidence in support of the original work by Storm et al. In “Experiment 1”, using the same paradigm as that used by Storm et al. and Callahan, the effect of retrieval-induced forgetting was repeatedly produced and eliminated when participants engaged in successive rounds of retrieval practice and restudy, respectively.

The finding that retrieval-induced forgetting is eliminated by restudy was replicated in “Experiment 2”, with participants this time receiving three rounds of retrieval practice prior to restudy. Specifically, a single re-exposure to the initially studied items was sufficient to eliminate the effect of retrieval-induced forgetting produced by three rounds of

retrieval practice. This finding is important because most published studies on retrieval-induced forgetting to date have employed designs involving three rounds of retrieval practice, a design feature that typically leads to larger effects of retrieval-induced forgetting, and that could have made the retrieval-induced forgetting effect relatively more robust to being eliminated by restudy.

From a theoretical perspective, the current findings are consistent with the idea that re-exposure to inhibited items prior to final test can release those items from the effects of inhibition. Specifically, even if Rp– items are inhibited by retrieval practice, they can regain their accessibility (relative to what it would have been had they not been inhibited) if they are restudied between retrieval practice and final test. This finding is important in that it is consistent with the idea that retrieval-induced forgetting is ephemeral in nature, and that the mechanisms underlying retrieval-induced forgetting do not cause permanent or lasting impairment to the way in which Rp– items are represented in memory.

Of course, an absence of evidence is not evidence of absence, and it is entirely possible that retrieval can cause forgetting in a way that is lasting—perhaps involving the mechanisms of reconsolidation—but that the methods used in the current study were not sensitive to such dynamics. It is also worth noting that the mechanisms of inhibition may be distinct from the mechanisms that allow the aftereffects of inhibition to persist (Anderson, 2003). Although immediate re-exposure to studied items after retrieval practice may eliminate retrieval-induced forgetting, more delayed re-exposure, such as after reconsolidation processes have had time to take place, may be less likely to eliminate retrieval-induced forgetting. We encourage researchers to consider the general possibility of reconsolidation playing a role in retrieval-induced forgetting more closely in future research, both within and beyond the context of the retrieval-practice paradigm.

Whereas the current results are clearly consistent with the inhibition account of retrieval-induced forgetting, they are somewhat less consistent with other, non-inhibition accounts. If Rp– items are less recallable than Nrp items because of strength-based associative interference, for example, then why would the effect of retrieval-induced forgetting be completely undone by a single opportunity to restudy the studied items prior to final test? Presumably, the Rp+ items strengthened by retrieval practice would have remained strengthened after the restudy of Rp– items and Nrp items—and they should have, therefore, continued to interfere with the recall of Rp– items on the final test (even if to a relatively lesser extent than they would have in the non-restudy condition). Said differently, if strength-based interference is sufficient to cause retrieval-induced forgetting, then we should have observed at least some evidence of retrieval-induced forgetting in the restudy condition. The fact that

the retrieval-induced forgetting effect was eliminated by restudy suggests that the forgetting effect we observed was not caused by strength-based interference. One prediction might be that the degree to which retrieval-induced forgetting is eliminated following restudy depends on the extent to which non-inhibitory factors are adequately controlled. A final test that employs item-specific cues and that controls for output interference (e.g., category-plus-stem-cued recall or item recognition), for example, may be more likely to observe an elimination of retrieval-induced forgetting following restudy than a final test that does not (e.g., category-cued recall).

It remains to be seen whether the current findings generalize to other iterations of the retrieval-practice paradigm. It is possible, for example, that repeated retrieval practice over extended periods of time (e.g., days and weeks), the use of different kinds of study materials (e.g., novel episodic associations), or even sleep following retrieval practice (see Abel & Bäuml, 2012; Racsmány et al., 2009), create conditions in which retrieval practice updates memory in a way that cannot be easily undone. The type of retrieval practice may also matter. It is worth noting that Hulbert and Norman (2015) found a large reversal effect following restudy using a within-list retrieval practice design. Indeed, for reasons specified in their neural differentiation account, the reversal effect (with Rp— items becoming relatively more recallable than Nrp items following restudy) may be stronger in studies using a within-list retrieval practice design than in studies using an extra-list retrieval practice design.

The finding that Rp— items benefit significantly more from restudy than Nrp items is consistent with one of the central assumptions of the New Theory of Disuse (Bjork & Bjork, 1992). According to the New Theory of Disuse, the benefits of restudy (both in terms of increasing retrieval strength and producing new storage strength) can be enhanced by manipulations that reduce retrieval strength prior to restudy (for related evidence, see Bjork & Allen, 1970; Cuddy & Jacoby, 1982; Dempster, 1996; Smith et al., 1978). In the context of the retrieval-practice paradigm, by virtue of their inhibited retrieval strength, Rp— items stand to benefit more from restudy than Nrp items. Indeed, this forgetting-enhanced new learning effect may partly explain why restudy has the potential to not only eliminate, but reverse, the effect of retrieval-induced forgetting.

Finally, it is not immediately obvious why the current results, and those reported by Storm et al. (2008), differ so markedly from those reported by Callahan (2015). One possibility is that there were subtle differences in the way the studies were run, such as in the way participants were recruited or instructed to complete the task. Another possibility is that Callahan's study was not appropriately counterbalanced, a possibility that seems plausible given the materials posted on OSF. Ultimately, the current study was not designed to address the discrepancy in the previous results. What the

current study does provide is more substantial evidence that retrieval-induced forgetting can be eliminated by restudy. Future research should investigate the potential source of the discrepant results more closely, especially if the pattern of results reported by Callahan is observed once again.

Concluding comments

Whether, when, and to what extent, retrieval-induced forgetting becomes diminished or eliminated remains a topic of ongoing debate. Even if retrieval-induced forgetting can be shown to be eliminated with the passage of time; however, such a finding would not necessarily speak to the theoretical mechanism underlying that elimination. To quote a famous line by McGeoch (1932, p. 144): “In time all events occur, but to use time as an explanation would be to explain in terms so perfectly general as to be meaningless... Time, in and of itself, does nothing. It contributes, rather, a logical framework in terms of which we can describe the sequence of observed events.” Thus, to explore the mechanisms by which retrieval-induced forgetting becomes diminished, researchers should focus on factors that occur with time, and not on the construct of time itself. To this end, the present results are consistent with the idea that retrieval-induced forgetting reflects a somewhat fleeting or ephemeral phenomenon, one that can be undone when items are restudied. Future work will be necessary to illuminate the conditions under which retrieval can have a more powerful and lasting impact on the ability to remember information that is not retrieved.

Availability of data and material The data can be found on the Open Science Framework at <https://osf.io/dp8cu/files/>.

Code availability Not applicable.

Declarations

Conflict of interest Authors declares that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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