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# Retrieval-induced forgetting: Dynamic effects between retrieval and restudy trials when practice is mixed

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**Abstract** Results from numerous previous studies suggest that when subjects study items from different categories and then repeatedly retrieve, or restudy, some of the items from some of the categories, repeated retrieval, but not repeated study, induces forgetting of related unpracticed items. We investigated in two experiments whether such effects of pure retrieval and pure study practice generalize to mixed practice—that is, when retrieval and restudy trials are randomly interleaved within a single experimental block. Experiment 1 employed cued recall; Experiment 2 employed item recognition testing. In both experiments, pure repeated retrieval, but not pure repeated study, caused forgetting of related unpracticed items, which is consistent with the prior work. In contrast, with mixed practice, both retrieval and restudy induced forgetting. Thus, whereas retrieval caused forgetting regardless of practice mode, restudy caused forgetting with mixed practice, but not with pure practice. The finding provides first evidence for dynamic effects between retrieval and restudy trials when practice is mixed. It is consistent with the view that, with mixed practice, subjects engage in more retrieval during restudy trials, so that restudy trials may trigger similar processes as retrieval trials and, thus, induce forgetting of related, not restudied, items.

**Keywords** Episodic memory · Retrieval-induced forgetting · Retrieval practice · Restudy

Selective retrieval of some memories can impair subsequent recall of related memories. Such retrieval-induced forgetting has repeatedly been demonstrated using the retrieval practice paradigm (Anderson, Bjork, & Bjork, 1994). In this

paradigm, subjects often study items from different semantic categories (e.g., ANIMAL–horse, FRUIT–banana, ANIMAL–bear) before they are asked to repeatedly retrieve half of the items from half of the categories (e.g., ANIMAL–ho\_\_\_\_\_). The typical finding in this paradigm is that, on a later category-cued recall test, memory performance for practiced items (e.g., horse) is enhanced, but memory performance for unpracticed items from the practiced categories (e.g., bear) is impaired, relative to the control items from the unpracticed categories (e.g., banana). The two retrieval practice effects have been found over a wide range of materials, including verbal (e.g., Anderson et al., 1994), visual (Ciranni & Shimamura, 1999), and autobiographical (Barnier, Hung, & Conway, 2004) materials, as well as over a wide range of memory tasks, including word stem completion (e.g., Anderson et al., 1994; Bäuml & Aslan, 2004), tests employing so-called independent probes—that is, new retrieval cues that were not used in previous phases of the experiment (e.g., Anderson & Spellman, 1995; Saunders & MacLeod, 2006)—and item recognition (e.g., Hicks & Starns, 2004; Spitzer & Bäuml, 2007; for reviews, see Anderson, 2003; Bäuml, Pastötter, & Hanslmayr, 2010; Storm & Levy, 2012; for recent evidence on the beneficial effects of selective memory retrieval, see Bäuml & Samenieh, 2010, 2012).

Retrieval-induced forgetting has proven to be a recall-specific effect and to typically arise if subjects actively retrieve the to-be-practiced items, but not if they just strengthen these items through reexposure. Ciranni and Shimamura (1999) reported such a pattern using visual materials. Subjects learned the locations of uniquely colored items that could be categorized by shape. Retrieval practice on the locations of half of the objects from a shape category facilitated memory performance for practiced items but impaired recall of the unpracticed objects' locations. In contrast, a second practice condition, in which a subset of the

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items was repeatedly reexposed instead of being retrieval-practiced, induced recall improvement for the practiced items but no forgetting of the related unpracticed items. Similar demonstrations have been reported in numerous other studies employing verbal materials (e.g., Anderson, Bjork, & Bjork, 2000; Bäuml, 2002; Bäuml & Aslan, 2004; Hanslmayr, Staudigl, Aslan, & Bäuml, 2010; for an exception, see Raaijmakers & Jakab, 2012). Together, the results have been taken as support for the view that retrieval-induced forgetting is not caused by increased competition arising from the strengthening of practiced items but by inhibitory control mechanisms operating during retrieval practice (Anderson & Spellman, 1995). According to this account, during retrieval practice, a category's not-to-be-practiced items interfere and, as a consequence, are inhibited to reduce interference and make selection of the target information easier (for noninhibitory accounts of retrieval-induced forgetting, see Camp, Pecher, & Schmidt, 2007; Jakab & Raaijmakers, 2009; Perfect et al., 2004).

Practice effects, as they have been examined in the retrieval practice paradigm, are theoretically interesting because they provide information about the beneficial and detrimental effects of retrieval and restudy and their underlying mechanisms, and they are of practical relevance because both retrieval and restudy play an important role in educational settings (see literature on the testing effect; e.g., Karpicke & Roediger, 2008; Roediger & Karpicke, 2006). However, to date, practice effects have been examined exclusively employing pure practice conditions. In fact, in some studies, one group of the subjects were engaged in retrieval practice trials, whereas another group completed restudy trials (e.g., Anderson et al., 2000; Bäuml, 2002; Bäuml & Aslan, 2004; Ciranni & Shimamura, 1999). In other studies, type of practice was manipulated within subjects, and subjects were engaged in retrieval practice trials in one experimental block and in restudy trials in another, separate block (e.g., Johansson, Aslan, Bäuml, Gäbel, & Mecklinger, 2007; Hanslmayr et al., 2010; Wimber, Rutschmann, Greenlee, & Bäuml, 2009). However, in none of the studies was practice mixed so that retrieval practice and restudy trials would be randomly interleaved within a single experimental block. Thus, the question arises of whether the findings from pure retrieval and pure restudy practice generalize to mixed practice situations.

Results of a previous study examining the effects of retrieval and reexposure of some studied items on later recall of the remaining studied items suggest that mixed practice might affect the influence of retrieval and restudy on memory of related items. In this prior work, Bäuml and Aslan (2004) replicated the basic finding that retrieval practice on a subset of previously studied items can impair recall of the list's remaining items. In particular, they showed that

the effect of reexposure of some of the studied items on later recall of remaining list items can vary with the setting of the task. When subjects were instructed to use reexposure of items to enhance their learning of the reexposed items, reexposure did not affect recall of the remaining items. In contrast, when subjects were instructed to use the reexposed items as retrieval cues for recall of the remaining items, reexposure impaired recall of the remaining items. This pattern arose both when there was a delay between reexposure and test and when reexposure occurred immediately before the recall test. Because the two reexposure conditions did not differ in material and procedural detail, the findings indicate that the effect of reexposure can depend on task setting, inducing no forgetting of related materials in a restudy context but inducing forgetting of the materials in a retrieval context.

Although Bäuml and Aslan's (2004) finding *per se* does not imply that mixed practice can influence the effect of restudy on recall of related, not restudied items, it raises such a possibility, at least if mixed practice creates some dynamic effects between retrieval and restudy trials. Numerous studies examining task switching have shown that switching back and forth between single tasks can cause switching effects, leading to impaired processing of stimuli after switching (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995). Moreover, such dynamic effects can be asymmetric: With switching between tasks varying in difficulty, there is often a larger switching effect for the easy task than for the difficult task (Allport et al., 1994), as has been observed with various combinations of tasks, such as, for instance, switching between first and second languages in bilinguals (Campbell, 2005; Meuter & Allport, 1999). Switching back and forth between (more effortful) retrieval trials and (less effortful) restudy trials may also cause asymmetric dynamic effects, and subjects, for instance, may engage in more retrieval during restudy trials when the trials are mixed than when restudy trials occur in the absence of intermittent retrieval trials. If so, with mixed practice, reexposure trials might trigger similar processes as retrieval trials, creating beneficial effects for the restudied items but detrimental effects for the related, not reexposed items. In such cases, pure and mixed practice might not differ in the effects of retrieval practice, but they might differ in the effects of restudy. The issue of possible dynamic effects between retrieval and restudy trials has not been addressed in the literature to date.

The present study reports the results of two experiments designed to examine whether the effects of retrieval and restudy in pure practice conditions differ from the effects of retrieval and restudy in a mixed practice condition. In both experiments, a variant of the retrieval practice paradigm was employed. In Experiment 1, subjects studied a categorized list of items followed by an intermediate

practice phase, in which they were asked to repeatedly retrieve some of the previously studied items from some of the studied categories, to repeatedly restudy some of the items from some of the categories, or to repeatedly retrieve some items from some categories of the study list and to repeatedly restudy other items from other categories of the list in random order. After a short distractor task, memory for all initially studied items was tested employing a cued recall test. In Experiment 2, again subjects studied a categorized item list before completing a practice phase. In the blocked practice condition, subjects first repeatedly retrieved some of the previously studied items from some of the categories and then repeatedly restudied other items from other categories of the list, or vice versa. In the mixed practice condition, subjects again retrieval-practiced some of the previously studied items from some of the categories and restudied other items from other categories, but this time, retrieval and restudy trials were interleaved in random order. After completing a distractor task, an item recognition test based on confidence ratings was applied.

Following prior work that indicates that retrieval-induced forgetting is a recall-specific effect (e.g., Anderson et al., 2000; Ciranni & Shimamura, 1999), we expected, in both experiments, forgetting of the unpracticed items from the practiced categories in the pure retrieval condition, but not in the pure restudy condition. In contrast, in the mixed practice conditions of the two experiments, one may expect forgetting of both the unpracticed items from the retrieval-practiced categories and the unpracticed items from the restudied categories. Such expectation may arise from the view that the effect of reexposure can depend on the setting of the task (Bäuml & Aslan, 2004), and the suggestion that switching between retrieval and restudy trials may lead subjects to engage in more retrieval during restudy trials, so that restudy trials may trigger processes similar to those for retrieval trials and, thus, induce forgetting of related, not restudied items. The results of the two experiments will provide first evidence on possible dynamic effects between retrieval and restudy trials.

## Experiment 1

### Method

#### Subjects

Eighty-four undergraduates participated in the experiment (mean age = 22.87 years, range = 19–33 years), all of them speaking German as a native language. They took part in the experiment on a voluntary basis, were tested individually, and received a monetary reward for their participation.

### Materials

We constructed two study lists, each list consisting of words from nine semantic categories. Each category contained six exemplars, which were drawn from several published word norms (Battig & Montague, 1969; Mannhaupt, 1983; Scheithe & Bäuml, 1995). The two most frequent exemplars of each category were excluded. Because previous work showed that categories' high-frequency exemplars may be more susceptible to retrieval-induced forgetting than their low-frequency exemplars (e.g., Anderson et al., 1994; Bäuml, 1998), for each category, the three items with the lower word frequency (in the following, referred to as *low-frequency items*) were practiced during the intermediate practice phase, whereas the three items with the higher word frequency (in the following, referred to as *high-frequency items*) served as unpracticed items (see also Spitzer & Bäuml, 2007). Within each category, each item had a unique initial letter. Additionally, two exemplars from six other categories were used as buffer items in the study phase.

### Design

To replicate prior work with pure practice conditions, we used a mixed factorial design with the between-subjects factor of *practice type* (pure retrieval vs. pure restudy) and the within-subjects factor of *item type* (practiced vs. unpracticed vs. control). To investigate dynamic effects between retrieval and restudy trials, we implemented an additional mixed practice condition, in which retrieval practice and restudy were manipulated within subjects. All subjects went through three main phases: an initial study phase, an intermediate practice phase, and a final test phase. Experimental conditions differed in the intermediate practice phase only. In the pure retrieval condition ( $n = 24$ ), subjects were asked to repeatedly retrieve the low-frequency items of six of the nine categories; in the pure restudy condition ( $n = 24$ ), subjects repeatedly restudied the low-frequency items of six of the nine categories; in the mixed practice condition ( $n = 36$ ), subjects repeatedly retrieved the low-frequency items of three of the nine categories and repeatedly restudied the low-frequency items of three further categories. The order of the retrieval and restudy trials in the mixed practice condition was random, so that subjects did not know whether the next exemplar was to be restudied or to be retrieved. In each of the three conditions, the items of the three remaining categories served as control items; the categories' low-frequency items were used as control items for the practiced items, and the categories' high-frequency items served as baseline for the unpracticed items. Consequently, six different item types were created: practiced items from retrieval-practiced categories (rp+ items), practiced items from restudied categories (rs+ items), unpracticed items

from retrieval-practiced categories (rp- items), unpracticed items from restudied categories (rs- items), control items for the practiced items (c+ items), and control items for the unpracticed items (c- items). Across subjects, we counterbalanced which of the studied categories were retrieval-practiced, restudied, or served in a control condition. For each subject, the experiment consisted of two parts, which differed only in which of the two study lists was used. That is, after subjects had completed a study–practice–test cycle, they had a 10-min break before they were asked to complete another cycle with new word materials. The assignment of the two study lists to the two parts of the experiment was counterbalanced. The second cycle was run with the only goal being to increase the statistical power of the data.

### Procedure

In the study phase, each item was presented together with its category cue (e.g., TREE–*maple*, INSECT–*beetle*) at a rate of 4 s per item. The serial order of the items was block randomized; that is, six blocks were created, which were composed of one randomly selected item from each of the nine categories, with the restriction that no two items from the same category were presented in succession. Additionally, three buffer items were shown at the beginning and the end of the study list. After half of the subjects had been tested, the order of the study sequence was reversed. After the study phase, subjects were asked to count backward from 500 in steps of 3 for 60 s as a recency control.

In the intermediate practice phase, subjects were asked to practice the low-frequency items of six of the nine categories. For items of categories that should be retrieval-practiced (rp+ items), the item's initial letter was presented together with its category cue (e.g., TREE–*m*\_\_\_\_), and subjects were given 5 s to recall the corresponding word. Items that should be restudied in the practice phase (rs+ items) were presented together with their category cue (e.g., INSECT–*beetle*) for 5 s. The order of the items was again blocked randomized. Within each block, items were presented randomly, and the succession of the blocks was randomly drawn for each subject. After the first practice cycle, a second practice cycle was conducted, following the same procedure as in the first practice cycle. After the intermediate practice phase, the subjects completed a distractor task, in which they rated the attractiveness of international celebrities for 3 min.

In the final test phase, subjects were provided with the first letter of each studied word together with its category cue (e.g., INSECT–*b*\_\_\_\_) and were asked to write down the appropriate word in a test booklet within 7 s. The order of presentation was blocked by category. Because all of a

category's items had unique initial letters, output order could be controlled. For each category, the (unpracticed) high-frequency items were tested first, and the (practiced) low-frequency items second. Presentation order of the cues was random. The order of the categories was counterbalanced across subjects.

### Results

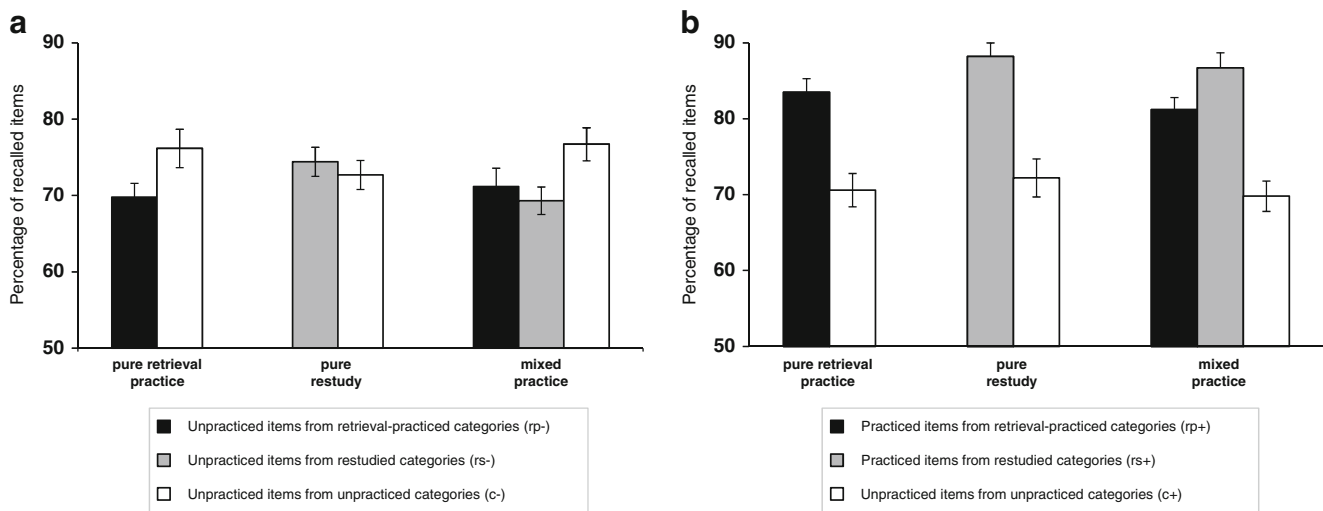
#### Practice phase

Mean success rates in the intermediate practice phase were high and did not vary with practice condition (pure retrieval, 81.73 %; mixed practice, 80.73 %),  $t(58) < 1$ .

#### Test phase

*Detrimental effects of practice* Figure 1a depicts percentage of recalled unpracticed items and their corresponding control items on the final test. For the two pure practice conditions, an ANOVA with the between-subjects factor of *practice type* (pure retrieval vs. pure restudy) and the within-subjects factor of *item type* (unpracticed vs. control) revealed no main effects of practice type,  $F(1, 46) < 1$ , and item type,  $F(1, 46) = 2.407$ ,  $MSE = .007$ ,  $p = .128$ , but a significant interaction of the two factors,  $F(1, 46) = 6.346$ ,  $MSE = .007$ ,  $p = .016$ , partial  $\eta^2 = .121$ . Post hoc tests showed that pure retrieval practice impaired recall of unpracticed items (rp- items) relative to the c- items, thus showing standard retrieval-induced forgetting,  $t(23) = 2.324$ ,  $p = .029$ ,  $d = .579$ , whereas pure restudy did not affect recall of unpracticed items (rs- items) relative to the c- items,  $t(23) = 0.831$ ,  $p = .415$ . In the mixed practice condition, an ANOVA with the within-subjects factor of item type revealed a significant main effect of item type,  $F(2, 70) = 4.584$ ,  $MSE = 0.012$ ,  $p = .013$ , partial  $\eta^2 = .116$ . Planned comparisons showed that, as compared with recall of the c- items, prior retrieval practice led to forgetting of rp- items,  $t(35) = 2.043$ ,  $p = .049$ ,  $d = .324$ , and prior restudy led to forgetting of rs- items,  $t(35) = 2.935$ ,  $p = .006$ ,  $d = .406$ ; rp- and rs- items did not differ in recall level,  $t(35) < 1$ .

The results of Fig. 1a suggest that the effect of prior retrieval practice on recall of the related unpracticed items did not vary between pure and mixed practice. Consistently, a  $2 \times 2$  ANOVA with the within-subjects factor of item type (rp- items vs. c- items) and the between-subjects factor of practice mode (pure retrieval vs. mixed practice) showed no significant interaction,  $F(1, 58) < 1$ . In contrast, the results of Fig. 1a suggest that the effect of prior restudy on recall of the related unpracticed items varied with practice mode. Consistently, a  $2 \times 2$  ANOVA with the within-subjects factor of item type (rs- items vs. c- items) and the between-subjects factor of practice mode (pure restudy vs. mixed



**Fig. 1** Recall percentages for unpracticed, practiced, and control items after pure retrieval practice, pure restudy, and mixed practice in Experiment 1. Error bars represent standard errors. **a** Results for the unpracticed and control items. **b** Results for the practiced and control items

practice) revealed a significant interaction,  $F(1, 58) = 6.701$ ,  $MSE = .009$ ,  $p = 0.12$ , partial  $\eta^2 = .104$ .

**Beneficial effects of practice** Figure 1b shows percentage of recalled practiced items and their corresponding control items on the final test. For the two pure practice conditions, an ANOVA with the between-subjects factor of practice type (pure retrieval vs. pure restudy) and the within-subjects factor of item type (practiced vs. control) revealed a significant main effect of item type,  $F(1, 46) = 67.373$ ,  $MSE = .007$ ,  $p < .001$ , partial  $\eta^2 = .594$ , no main effect of practice type,  $F(1, 46) = 1.749$ ,  $MSE = .014$ ,  $p = .192$ , and no interaction effect,  $F(1, 46) < 1$ . Post hoc tests showed that pure retrieval practice improved later recall of practiced items (rp+ items), as compared with c+ items,  $t(23) = 6.545$ ,  $p < .001$ ,  $d = 1.349$ , and pure restudy improved later recall of practiced items (rs+ items), as compared with c+ items,  $t(23) = 5.485$ ,  $p < .001$ ,  $d = 1.137$ . Regarding the mixed practice condition, an ANOVA with the within-subjects factor of item type revealed a significant main effect of item type,  $F(2, 70) = 30.488$ ,  $MSE = .009$ ,  $p < .001$ , partial  $\eta^2 = .466$ . Planned comparisons showed that all three item types differed significantly in recall level from each other: prior practice improved recall of rp+ items,  $t(35) = 5.012$ ,  $p < .001$ ,  $d = 0.941$ , as well as recall of rs+ items,  $t(35) = 7.789$ ,  $p < .001$ ,  $d = 1.597$ , as compared with c+ items, and recall of rs+ items was higher than recall of rp+ items,  $t(35) = 2.536$ ,  $p = .016$ ,  $d = 0.474$ . Both the beneficial effect of restudy and the beneficial effect of retrieval did not vary between pure and mixed practice [restudy,  $F(1, 58) < 1$ ; retrieval,  $F(1, 58) < 1$ ].

## Discussion

The results of Experiment 1 replicate prior work examining the beneficial and detrimental effects of (pure) retrieval practice

and (pure) restudy. In the pure retrieval condition, retrieval practice of a subset of the previously studied items led to improved recall of the retrieval practiced items and induced forgetting of related unpracticed items, relative to the control items. In the pure restudy condition, restudy of a subset of previously studied items facilitated recall of the restudied items but did not affect recall of related unpracticed items. Numerous previous studies reported the same pattern, pointing to retrieval-induced forgetting as a recall-specific effect (e.g., Anderson et al., 2000; Ciranni & Shimamura, 1999).

Going beyond the prior work, the present results show that, with mixed practice, retrieval practice of some items still causes beneficial effects on the practiced materials and detrimental effects on related unpracticed materials. With such practice, however, the effects of restudy mimic the effects of retrieval practice, improving recall of the restudied items but inducing forgetting of the related, not restudied materials. The finding that restudy induces detrimental effects on related items with mixed practice, but not with pure practice, provides the first demonstration of dynamic effects between retrieval and restudy conditions when practice is mixed. The goal of Experiment 2 was to replicate this pattern of results using item recognition rather than cued recall as the memory task.

## Experiment 2

### Method

#### Subjects

Forty-eight new subjects were tested in this experiment (mean age = 22.31 years, range = 18–30 years). All subjects

spoke German as a native language, took part on a voluntary basis, and received monetary reward for their participation. All of them were tested individually.

### Materials

Twelve exemplars from each of nine semantic categories were drawn from published word norms (Mannhaupt, 1983). The two most frequent exemplars of each category were excluded. Within each of the categories, six of the chosen exemplars were studied, whereas the remaining six items were used as lures in the later recognition test. According to their rank in the norms, the exemplars of each category were alternately assigned to the study list and the lure list. As in Experiment 1, for each category, the three study list items with the lower word frequency (low-frequency items) were practiced during the intermediate practice phase, whereas the three study list items with the higher word frequency (high-frequency items) served as unpracticed items. Within each category, each study item had a unique first letter. Additionally, two exemplars from three further categories were used as buffer items in the study and recognition test phases.

### Design

The experiment had a mixed factorial design with the between-subjects factor of *practice mode* (blocked practice vs. mixed practice), the within-subjects factor of *practice type* (retrieval vs. restudy), and the within-subjects factor of *item type* (practiced vs. unpracticed vs. control). As in Experiment 1, all subjects went through three main phases: an initial study phase, an intermediate practice phase, and a final recognition test phase. Again, experimental conditions differed in the intermediate practice phase only. In the blocked practice mode, subjects first repeatedly retrieved the low-frequency items of three of the nine categories before repeatedly restudying the low-frequency items of three further categories, or vice versa. In the mixed practice mode, subjects also retrieval-practiced the low-frequency items of three of the nine categories and restudied the low-frequency items of three further categories; this time, however, retrieval practice and restudy trials were not blocked but had a random order. The blocked practice mode mimics the two pure practice conditions employed in Experiment 1, whereas the mixed practice mode is identical to the one employed in Experiment 1. In each of the two practice modes, the items of the three remaining categories served as control items. Consequently, the same two practiced item types (rp+ and rs+ items), the same two unpracticed item types (rp- and rs- items), and the same two control item types (c+ and c- items) as in Experiment 1 were created. Additionally, because of the final recognition test, the design

created three types of new items: lures from retrieval-practiced categories (rp lures), lures from restudied categories (rs lures), and lures from unpracticed control categories (c lures). Across subjects, we counterbalanced which of the studied categories was retrieval-practiced, restudied, or served in a control condition.

### Procedure

The study phase and the intermediate practice phase were identical to the study and the intermediate practice phases of Experiment 1, with the only exception that subjects in Experiment 2 completed a blocked practice phase, including a block of to-be-retrieved and a block of to-be-restudied items, rather than two pure practice conditions as employed in Experiment 1. After the intermediate practice phase, the subjects completed a distractor task, in which they worked on Raven's progressive matrices for 8 min.

In the final test phase, subjects completed an old–new recognition test, in which they rated their confidence of a presented exemplar being old or new on a 6-point rating scale (1 = *definitely old*, 6 = *definitely new*). The responses were entered via the digits on the PC keyboard and were recorded automatically in a log file. The subjects were asked to use the whole range of the rating scale. Each exemplar was presented together with a schematically depicted rating scale in the lower part of the screen. As soon as the subject had entered any allowed digit, the next exemplar was presented on the screen. The order of the items was block-randomized, with two constraints: Neither old materials nor lures appeared more than three times in a row; the unpracticed materials and their corresponding control items mixed with lures were presented in the first half of the test phase, whereas the practiced materials and their corresponding control items mixed with lures in the second. At the beginning of the test phase, three practice trials with old and new buffer items occurred.

### Statistical analysis

We used a signal detection approach to analyze the recognition data (e.g., Macmillan & Creelman, 2004). For this, hit and false alarm rates were cumulated over the different criterion points, starting with the most confident criterion point (i.e., 1 = *definitely old*). To account for the characteristic shape of recognition receiver operating characteristics (ROCs), which are usually asymmetrical along the diagonal, it is often assumed that the variance of the strength distribution for studied items exceeds the variance of the distribution for unstudied items, and the unequal-variance signal detection model is applied to describe the data (e.g., Dunn, 2004; Wixted, 2007). According to this model, recognition in the present experiment was based on a single source of



memorial information (i.e., [general] memory strength),<sup>1</sup> and subjects responded with a given level of confidence whenever their assessment of the memory strength of a presented item exceeded the response criterion,  $c_i$ , associated with that confidence level. Studied items' memory strength is then given by the distance between the means of the underlying strength distributions for those studied items and the lures ( $d'$ ). When applied to 5-point ROC data, this model has seven free parameters (memory strength of studied items  $d'$ , variance of the strength distribution for studied items  $\sigma$ , and five response criteria  $c_1$ – $c_5$ ) and, thus, three degrees of freedom for statistically testing its goodness of fit. The model parameters were estimated using maximum likelihood techniques, which also allow for statistical testing (for technical details, see the Appendix in Spitzer & Bäuml, 2007).

Concretely, it was tested, in the first step, whether the unequal-variance signal detection model was able to describe the data for the single item type and practice conditions. If the model fitted the single data sets, it was analyzed in the second step, whether parameter  $d'$  varied significantly across item type and practice conditions; differences in  $d'$  across conditions suggest differences in memory strength and, thus, allow conclusions about possible beneficial and detrimental effects of practice. Specifically, for each practice condition, it was examined whether  $d'$  was higher for practiced than for control items and was lower for unpracticed than for control items. If reliable differences between item types arose, it was further tested whether the differences varied significantly across practice conditions.

## Results

### Practice phase

Mean success rates in the intermediate practice phase were high and did not vary with practice mode (blocked practice, 71.8 %; mixed practice, 75.9 %),  $t(46) < 1$ .

### Recognition test

*Detrimental effects of practice* Figures 2a and b depict the ROCs obtained by plotting the cumulative false alarm rates against the hit rates for each of the unpracticed item types and the corresponding control items, separately for the blocked (a) and mixed (b) practice mode. In addition, the figure shows the fit of the unequal-variance signal detection model to each single data set. Table 1 shows

the goodness-of-fit statistics and maximum-likelihood parameter estimates for the unpracticed items and their corresponding control items.

The unequal-variance signal detection model described the data for the two unpracticed item types (rp– and rs– items) and the control items (c–) in both practice modes (blocked practice, mixed practice) well, all  $\chi^2_s(3) < 5.88$ , all  $ps > .12$ . Analysis of whether the model parameters varied with item type revealed standard retrieval-induced forgetting in both practice modes; in fact,  $d'$  was significantly lower for rp– than for c– items, both in the mixed practice mode,  $\chi^2(1) = 9.51$ ,  $p = .002$ , and in the blocked practice mode,  $\chi^2(1) = 5.02$ ,  $p = .025$ ; the detrimental effect did not vary with practice mode,  $\chi^2(1) = 1.22$ ,  $p = .269$ . A different pattern arose for the rs– items: After mixed practice,  $d'$  was lower for rs– than for c– items,  $\chi^2(1) = 5.69$ ,  $p = 0.17$ , and no difference between rs– and rp– items was found,  $\chi^2(1) = 0.48$ ,  $p = .503$ , suggesting that restudy induced forgetting in the mixed practice mode. In contrast, after blocked practice, no difference in  $d'$  between rs– and c– items was observed,  $\chi^2(1) = 0.55$ ,  $p = .460$ , and  $d'$  was significantly higher for the rs– than for the rp– items,  $\chi^2(1) = 8.31$ ,  $p = .004$ , indicating that no forgetting of rs– items took place after blocked practice. The effect of restudy on related unpracticed items varied reliably with practice mode,  $\chi^2(1) = 5.18$ ,  $p = .023$ .<sup>2</sup>

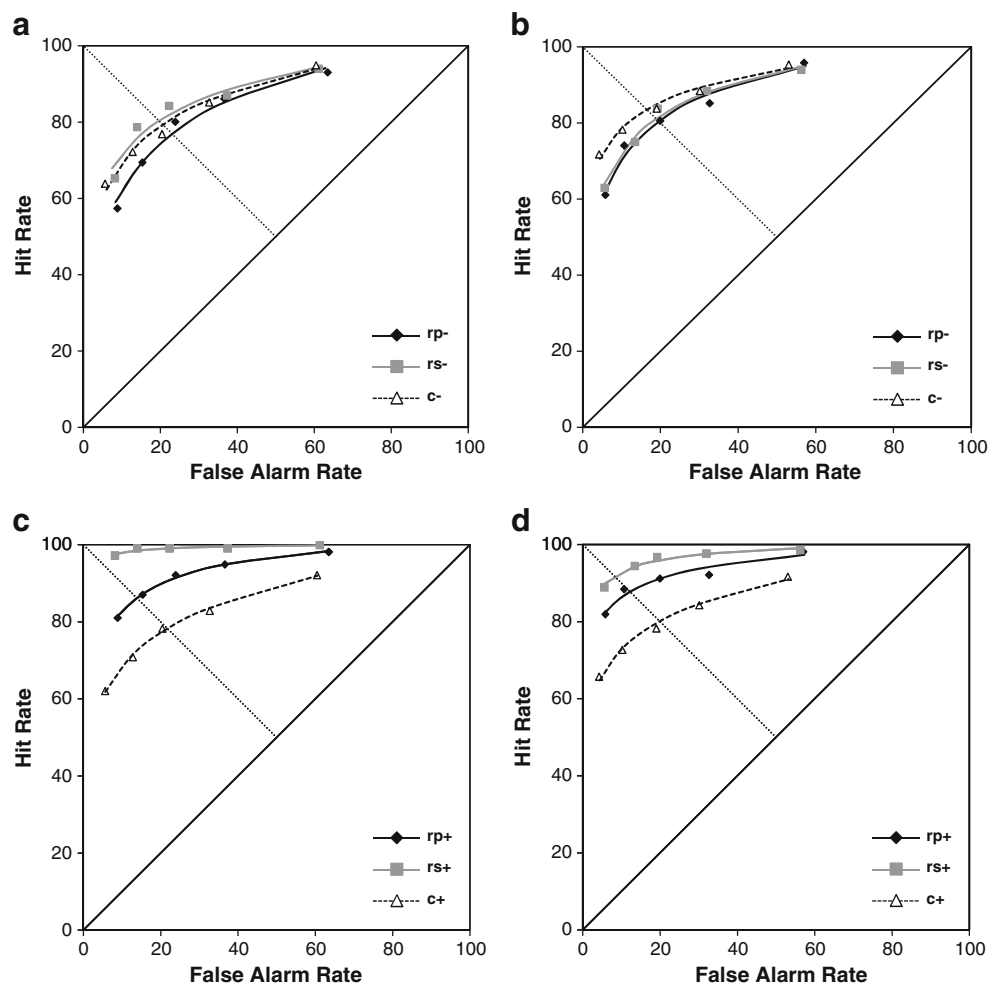
*Beneficial effects of practice* Figures 2c and d depict the ROCs obtained by plotting the cumulative false alarm rates against the hit rates for each of the practiced item types and the corresponding control items, separately for the blocked (c) and mixed (d) practice mode. In addition, the figure shows the fit of the unequal-variance signal detection model to each single data set. Table 1 shows the goodness-of-fit statistics and the maximum-likelihood parameter estimates for the practiced items and their corresponding control items.

Again, the unequal-variance signal detection model described the data for the two practiced item types (rp+ and rs+ items) and the control items (c+ items) in both practice modes (blocked practice, mixed practice) well, all  $\chi^2_s(3) < 5.02$ , all  $ps > .17$ . Statistical testing revealed improved memory for practiced items. Indeed,  $d'$  was significantly higher for rp+ than for c+ items, in both the mixed practice mode,  $\chi^2(1) = 5.82$ ,  $p = .016$ , and the blocked practice mode,  $\chi^2(1) = 3.99$ ,  $p = .046$ ; this beneficial effect did not vary with practice mode,  $\chi^2(1) = 0.492$ ,  $p = .483$ . Similarly,  $d'$  was significantly higher for rs+ than for c+ items, in both the mixed practice mode,  $\chi^2(1) = 10.59$ ,  $p = .001$ , and the

<sup>1</sup> The suggestion of a general memory strength dimension does not imply a single underlying memory process but, for instance, may reflect the additive combination of familiarity and recollection codes (e.g., Kelley & Wixted, 2001; Wixted & Stretch, 2004).

<sup>2</sup> In the blocked practice condition, half of the subjects did retrieval first and restudy second, whereas the other half did restudy first and retrieval second, which raises the question of whether block order might have affected results for unpracticed items. Corresponding analysis showed that there were no significant effects of block order, all  $\chi^2_s(1) < 2.66$ , all  $ps > .10$ .

**Fig. 2** Item recognition receiver operating characteristics (ROCs) depicting the cumulative hit and false alarm rates for the different item types in the two practice modes (blocked practice, mixed practice) of Experiment 2. Solid lines indicate theoretical ROCs predicted by the unequal-variance signal detection model. **a** ROCs for the two unpracticed item types (rp<sup>-</sup>, rs<sup>-</sup>) and the control items (c<sup>-</sup>) in the blocked practice mode. **b** ROCs for the two unpracticed item types (rp<sup>-</sup>, rs<sup>-</sup>) and the control items (c<sup>-</sup>) in the mixed practice mode. **c** ROCs for the two practiced item types (rp<sup>+</sup>, rs<sup>+</sup>) and the control items (c<sup>+</sup>) in the blocked practice mode. **d** ROCs for the two practiced item types (rp<sup>+</sup>, rs<sup>+</sup>) and the control items (c<sup>+</sup>) in the mixed practice mode



blocked practice mode,  $\chi^2(1) = 21.08, p < .001$ ; this beneficial effect also did not vary with practice mode,  $\chi^2(1) = 1.935, p = .164$ . After blocked practice,  $d'$  was higher for rs<sup>+</sup> than for rp<sup>+</sup> items,  $\chi^2(1) = 8.78, p < .001$ , whereas, despite an analogous numerical trend, no reliable difference in  $d'$  between rs<sup>+</sup> and rp<sup>+</sup> items was found after mixed practice,  $\chi^2(1) = 0.80, p = .372$ .<sup>3</sup>

**Discussion**

The results of Experiment 2 replicate the main findings of Experiment 1. With blocked practice, retrieval practice

improved recognition of the practiced items but induced forgetting of related unpracticed items; in contrast, restudy of a subset of previously studied items improved recognition of the restudied materials but did not affect memory for related but not restudied items. With mixed practice, again both retrieval practice and restudy improved memory for the practiced items; however, this time, both practice types induced forgetting of the related unpracticed materials. This pattern mimics the results of Experiment 1 and generalizes them from recall to item recognition. The results indicate that retrieval practice causes forgetting regardless of practice mode, whereas restudy causes forgetting with mixed practice, but not with pure/blocked practice. The findings of Experiment 2 thus provide another demonstration of the possible dynamic effects between restudy and retrieval practice.

**General discussion**

This study examined the effects of retrieval practice and restudy on related unpracticed materials, using both recall

<sup>3</sup> We also fitted the equal-variance signal detection model to the data. This model is identical to the unequal-variance model, with the constraint that the variance of the strength distribution for studied items is assumed to equal the variance of the distribution for unstudied items. The equal-variance model did not describe the ROCs as well as the unequal-variance model did. The equal-variance model described the data of two item types (rp<sup>+</sup> and rs<sup>+</sup> items) in the blocked practice condition, but not as well as the unequal-variance model did, all  $\chi^2_s(4) < 8.58$ , all  $ps > .073$ . For all other item types, the equal-variance signal detection model had to be rejected, all  $\chi^2_s > 12.64$ , all  $ps < .013$ .

**Table 1** Unequal-variance signal detection model for Experiment 2

Blocked practice					
Item type	Parameter estimates		Goodness of fit		
	$d'$	$\sigma$	$\chi^2$	$df$	$p$
rp−	1.68*	1.28	3.38	3	.336
rs−	2.16	1.53	5.88	3	.118
c−	2.02	1.47	2.46	3	.483
rp+	2.59*	1.37	0.44	3	.932
rs+	4.79*	1.72	4.27	3	.234
c+	2.09	1.68	0.48	3	.944
Mixed practice					
Item type	Parameter estimates		Goodness of fit		
	$d'$	$\sigma$	$\chi^2$	$df$	$p$
rp−	1.98*	1.32	4.17	3	.244
rs−	2.09*	1.38	2.63	3	.452
c−	2.62	1.69	1.73	3	.631
rp+	3.21*	1.76	5.02	3	.170
rs+	3.67*	1.63	2.39	3	.495
c+	2.41	1.86	0.94	3	.816

Note. rp− = unpracticed items from retrieval-practiced categories; rs− = unpracticed items from restudied categories; c− = unpracticed items from unpracticed categories; rp+ = practiced items from retrieval-practiced categories; rs+ = practiced items from restudied categories; c+ = unpracticed items from unpracticed categories;  $d'$  = general memory strength;  $\sigma$  = variance of the target distribution.

\* Significant deviations from control performance ( $p < .05$ ).

and recognition testing. The results of Experiments 1 and 2 replicate prior work on retrieval-induced forgetting by showing beneficial effects of retrieval practice on practiced materials and detrimental effects of retrieval practice on related unpracticed materials, relative to control items, in both recall and item recognition tasks (e.g., Anderson et al., 1994; Anderson & Spellman, 1995; Hicks & Starns, 2004; Spitzer & Bäuml, 2007). As in the prior work, these effects were found with pure retrieval practice (i.e., when retrieval practice occurred in a separate experimental block), but equivalent effects arose also with mixed practice (i.e., when subjects retrieval-practiced some items on some of the practice trials and restudied other items on other trials of the experimental block). The results thus provide a further demonstration of the very robust beneficial and detrimental effects of retrieval practice.

The results of Experiments 1 and 2 also replicate prior work on the effects of restudy in the modified retrieval practice paradigm, showing that restudy of some previously studied items is beneficial for the restudied items but can leave memory for related unpracticed materials unaffected, in both recall and item recognition tasks (e.g., Anderson et al., 2000; Bäuml, 2002; Ciranni & Shimamura, 1999). Importantly, this pattern was present only with pure practice—that is, when restudy of some of the previously

studied items occurred in a separate experimental block. In contrast, with mixed practice—that is, when retrieval and restudy trials were randomly interleaved—a different picture arose, and restudy induced detrimental effects on related but not reexposed materials. Obviously, the effect of restudy on related materials can vary with the setting of the task and can be absent with pure practice but be present with mixed practice.

The present results provide first evidence for possible dynamic effects between retrieval and restudy trials. While the effects of retrieval seem to be robust and to not depend on practice mode, the effects of restudy appear to be less robust and to vary with the setting of the task. Indeed, the results show clear differences in the effects of restudy and retrieval practice with pure practice, but no such differences with mixed practice. The finding is consistent with the view that, with mixed practice, in which subjects have to switch back and forth between (more effortful) retrieval trials and (less effortful) restudy trials, dynamic effects arise that influence the processing of items after switching, particularly after switching from retrieval to restudy trials (e.g., Campbell, 2005; Meuter & Allport, 1999). In such cases, subjects may engage in more retrieval during restudy trials, causing the reexposure of the single items to impair memory for related unpracticed materials, in a way very similar to how retrieval practice does. The finding is in line with prior work, which also showed detrimental effects of reexposure in a retrieval context, but not in a restudy context (Bäuml & Aslan, 2004).

In principle, different detrimental effects of restudy with pure and mixed practice might arise if the two practice modes led to different degrees of beneficial effects for the restudied items (e.g., Mensink & Raaijmakers, 1988; Rundus, 1973). Indeed, if the beneficial effect of restudy was higher with mixed than with pure practice, one could argue that the detrimental effect with mixed practice arose because of enhanced competition from the restudied items at test. However, neither in Experiment 1 nor in Experiment 2 did mixed practice induce larger beneficial effects for restudied items than pure practice did, indicating that the present finding was not caused by differences in competition at test. Moreover, in Experiment 1, unpracticed items were tested first within their category, and in Experiment 2, subjects rated the unpracticed items mixed with lures in the first half of the recognition test and the practiced items mixed with lures in the second. Thus, in both experiments, output order was controlled, preventing the detrimental effects from being induced by tested-first practiced items causing forgetting of tested-last unpracticed items.

In the mixed practice conditions of the present study, restudy was equivalent to retrieval practice with regard to the unpracticed items, whereas the same equivalence did not arise with regard to the practiced items. Indeed, in Experiment 1, the beneficial effect of practice was statistically larger after

restudy than after retrieval practice, and in Experiment 2, at least a similar numerical trend arose. Although such a difference between restudy and retrieval practice is not unusual (e.g., Roediger & Karpicke, 2006) and may be the result of the intact reexposure of the to-be-restudied items during practice, in comparison with the only partly successful retrieval practice of the to-be-retrieved items, an interesting question for future research might be whether restudied items in the mixed condition reveal parallels to retrieved items—for instance, by showing reduced forgetting after a delay. Indeed, several studies on the so-called testing effect observed that retrieval of previously studied materials, in comparison with (pure) restudy of the materials, largely reduces such delay-induced forgetting (e.g., Karpicke & Roediger, 2008; Roediger & Karpicke, 2006). Thus, if, with mixed practice, the effects of reexposure mimicked the effects of retrieval, reexposure with mixed practice might not only reduce memory for the related unpracticed materials, but also reduce delay-induced forgetting for the restudied materials as well.

According to the inhibitory account of retrieval-induced forgetting, during retrieval practice, a category's not-to-be-practiced items interfere and, as a consequence, are inhibited to reduce interference and make selection of the target information easier (e.g., Anderson & Spellman, 1995). The present results are consistent with this account. If, with mixed practice, subjects engage in retrieval during restudy trials, restudy might also trigger inhibitory processes and, thus, cause forgetting of the related unpracticed items in a way very similar to how retrieval does. Such restudy-induced inhibition, however, should be restricted to mixed practice and be absent with pure practice (e.g., Anderson et al., 2000; Ciranni & Shimamura, 1999), which is what the present results suggest.

The present results are also in line with noninhibitory accounts of retrieval-induced forgetting. According to the competition account (Camp et al., 2007; Jakab & Raaijmakers, 2009), for instance, retrieval practice strengthens the practiced items to a larger extent than restudy does, thus creating more interference at test for related unpracticed items after retrieval than after restudy trials. However, if, with mixed practice, subjects engage in retrieval during restudy trials, the restudied items in this condition may be strengthened to a similar degree as the retrieval practiced items, thus inducing increased interference and forgetting of the related not restudied items at test. Finally, according to the context-change account (Perfect et al., 2004), subjects create distinct learning contexts during study and retrieval practice, so that at test for practiced categories, but not for unpracticed categories, subjects focus their search on the practice context, which would improve recall of the practiced items but relatively impair recall of the unpracticed items. However, if subjects in the mixed condition engage in

retrieval during restudy trials, a new, distinct practice context may be created not only for retrieval practiced categories, but also for reexposed categories, which would induce the observed forgetting of the unpracticed items at test. The inhibitory and noninhibitory accounts of retrieval-induced forgetting have sometimes been difficult to tease apart (see Storm et al., 2012), and this study was not designed to resolve this issue.

In sum, examining pure practice conditions, in which subjects engage either in retrieval trials or in restudy trials, prior work has shown that typically retrieval, but not restudy, trials induce forgetting of related unpracticed items (e.g., Anderson et al., 2000; Ciranni & Shimamura, 1999), which is replicated in the present work. Examining also mixed practice conditions, the present study extends the results from the previous studies by reporting an exception to this “rule” and showing that restudy can also induce forgetting of related items, although only in the presence of intermittent retrieval. The finding is the first demonstration of dynamic effects between retrieval and restudy trials and opens the window into the more detailed study of the interplay between retrieval and restudy practice.

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