The testing effect for visual materials depends on pre-existing knowledge

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Abstract

Remembering facilitates future remembering. This benefit of practicing by active retrieval, as compared to more passive re-learning, is known as the testing effect, and is one of the most robust findings in the memory literature. However, it has typically been assessed using verbal materials such as word-pairs, sentences, or educational texts. We here investigate if memory for visual materials equally benefits from retrieval-mediated learning. Based on cognitive and neuroscientific theories, we hypothesise that testing effects will be limited to meaningful visual images that can be related to pre-existing knowledge. In a series of four experiments, we systematically varied the type of material (meaningful object images vs non-meaningful “squiggle” shapes), the format of the test used to probe memory (a more visually driven alternative forced-choice test vs a remember/know recognition test), and the delay of the final test (immediate vs 1 week delay). We found that abstract shapes never showed a significant testing benefit, irrespective of test format, and even benefitted more from restudy than retrieval at longer delays, where testing effects are typically most prominent. Meaningful object images did benefit from testing, particularly at long delays, and with a test format probing the recollective component of recognition memory. Together, our results indicate that retrieval enhances memory for visual materials only when they have a unique, distinct meaning. This pattern of results is predicted by cognitive and neurobiologically motivated theories proposing that retrieval’s benefits emerge through spreading activation in pre-existing semantic networks, producing better integrated and more easily accessible memory traces.

Keywords: retrieval-induced enhancement; visual stimuli; memory consolidation; recollection; schema

Introduction

It is safe to say that most students do not enjoy being tested on course materials. However, research unambiguously shows that testing benefits memory retention. More precisely, actively and repeatedly retrieving newly learned information enhances its long-term memory retention much more than other types of re-exposure, such as re-reading or restudying that same information (see Karpicke et al., 2017; Roediger & Karpicke, 2006a for reviews). This retrieval practice advantage is known as the testing effect. Retrieval benefits are highly robust, and most commonly found after a delay between practice and the memory test, while a restudy advantage is sometimes observed when memory is probed shortly after practice (e.g. Roediger & Karpicke, 2006b). Despite being one of the most robust effects in the memory literature, testing effects have largely been demonstrated using verbal materials. We here investigate if and under what conditions this retrieval benefit extends to memory for visual materials.

Being such a well-studied phenomenon, the lack of experiments assessing the testing effect using visual materials may be surprising. The vast majority of experiments in the literature used verbal stimuli, such as vocabulary word pairs, sentences, short narratives, or educational texts. A number of studies have attempted to replicate the effect with visuo-spatial materials but, with a few exceptions (see Discussion), they usually test participants' memory for an associated label or name, rather than their memory for the stimuli's visual features (Carpenter & DeLosh, 2005; Coppens et al., 2011; Jonker et al., 2018; Tse et al., 2010), or they use materials that can easily be verbalised (Carpenter & Kelly, 2012; Carpenter & Pashler, 2007; Guran et al., 2019; Herweg et al., 2018).

Understanding whether the testing effect extends to visual stimuli is a key question to further our understanding of the mechanisms underlying this effect, which is to this day very limited (Karpicke et al., 2017; Rowland, 2014). Some cognitive theories attribute testing benefits to a deeper, more concept-based processing during retrieval, compared to restudy (Carpenter, 2009, 2011; Congleton & Rajaram, 2012; Pyc & Rawson, 2010; Verhoeijen et al., 2012). This greater conceptual processing is thought to result from the co-activation of related information during retrieval. Whereas activation during restudy is largely limited to the reinstatement of the restudied item itself (Carpenter & Yeung, 2017; Sinclair & Barense, 2019), a retrieval cue – due to the imprecise nature of retrieval –

is thought to trigger activation that spreads beyond the exact target memory (Antony et al., 2017; Carpenter & Yeung, 2017; Sinclair & Barense, 2019). Co-activated items might then become part of an updated memory, and facilitate future access to the target because they serve as additional retrieval cues (*elaborative retrieval hypothesis*; Carpenter, 2009) or as a mediating link between cue and target (*mediator effectiveness hypothesis*; Pyc & Rawson, 2010). Congruent with this hypothesis, neuroimaging studies have shown that, compared to restudy, retrieval leads to greater activation of related memories (Ferreira et al., 2019; Jonker et al., 2018).

This spreading of activation can lead to qualitative changes in neural representations, as suggested by neurobiological accounts of retrieval-mediated learning (Ritvo et al., 2019; Sinclair & Barense, 2019). Representational changes are determined by the strength with which associated memories become co-active (Sinclair & Barense, 2019). If overlapping memories are strongly reactivated alongside the target memory, their connections are presumably strengthened, creating an integrated memory (Detre et al., 2013; Newman & Norman, 2010). Weak to medium co-activation is associated with little strengthening, or even a differentiation of overlapping memories (Antony et al., 2017; Detre et al., 2013; Newman & Norman, 2010; Ritvo et al., 2019). Bringing together cognitive and neurobiologically-inspired theories, we recently proposed that retrieval exerts its beneficial effects via a similar mechanism as offline (e.g. sleep-dependent) memory consolidation (Antony et al., 2017). In this framework, retrieval cues trigger the reactivation of a recently learned item in a hippocampal-neocortical network, facilitating the integration of this new item into pre-existing neocortical knowledge structures.

Given that all the above theories assume that the benefits of retrieval-mediated learning depend on the spread of activation to associated memories, we here asked if pre-existing related knowledge is a necessary condition for a testing effect to emerge. In other words, can retrieval only enhance meaningful information that can be linked to previously stored memories (either via semantic or episodic associations), or can memory for novel, meaningless images also be enhanced via testing?

We ran four behavioural experiments to assess whether memory for novel visual information can be strengthened via retrieval. In these experiments, participants studied words paired with images, which were either meaningless abstract shapes (*squiggles*; Experiments 1A and 1B) or meaningful

objects (e.g. a mug, a key, etc.; Experiments 2A and 2B). Subsequently, half of the participants in each experiment retrieved a subset of the word-image associations, while the other half restudied a subset. Both groups were then tested right after practice (immediate test for half of the items) and a week later (delayed test for the other half). The final test was either a 3-alternative forced-choice (3-AFC) memory test (Experiments A) or a remember-know recognition test (Experiments B). Thus, we systematically combined the type of material (meaningful or meaningless) with each final memory test format (3-AFC or remember-know) across the four experiments.

We hypothesised that the testing effect would be more pronounced: i) for images with distinctive semantic meaning and ii) in the delayed, compared to the immediate, final memory test, as often found in the testing effect literature (Coppens et al., 2011; Roediger & Karpicke, 2006b; Toppino & Cohen, 2009; van den Broek et al., 2014).

Experiment 1A

Method

Participants

Forty-eight participants ($M_{\text{age}} = 22.6$, $SD = 3.2$, 42 female) took part in this study. Sample size was chosen based on typical samples in previous testing effect studies (Guran et al., 2019; Herweg et al., 2018; Jonker et al., 2018; Sutterer & Awh, 2016; Wing et al., 2013). Participants were randomly assigned to one of two practice conditions, with a total of 24 participants assigned to retrieval and 24 to restudy. The participants were undergraduate or postgraduate students at the University of Birmingham and received either course credits or a monetary reward for their participation. All of them reported normal or corrected-to-normal vision and no history of neurological, psychological or psychiatric conditions. Previous to the start of the experiment, participants signed an informed consent form and at the end of the delayed test were debriefed on the aims of the study. The study was approved by the STEM Ethics Committee of the University of Birmingham.

Materials and procedure

In this experiment, we used 40 (36 critical, 4 used for a hurdle test) black abstract shapes (*squiggles*; Figure 1B, yellow square), kindly shared by Groh-Bordin et al. (2006), presented on white backgrounds. These stimuli can be found at <https://osf.io/6zf3t/>. Each *squiggle* was randomly paired with a word. Words were drawn from the MRC psycholinguistic database (https://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm), and had similar values of imageability ($M = 567.9$, $SD = 10.9$), concreteness ($M = 583.7$, $SD = 30.7$), and meaningfulness ($M = 447.4$, $SD = 31.1$; all three scales measured in a range of 100 to 700).

The experiment consisted of four main stages: study, practice (retrieval or restudy, manipulated between subjects), immediate memory test, and delayed memory test (Figure 1A). The immediate test took place immediately after practice, whereas the delayed test took place after 7 days.

During study, participants saw a word in black font at the top of the screen, with a *squiggle* (0.48 x 0.64 cm) below for 7 sec. Participants were instructed to link the word and the squiggle as well as they could, as they would be tested on the pairs later. In addition to memorising the pairs, participants were asked to press a key to indicate whether they found it easy or hard to link the word and the *squiggle* together (left for easy, right for hard). Since these meaningless shapes are difficult to memorise (as revealed in a pilot study), each pair was repeated twice during the study phase. The order of stimulus presentation was randomised, but all the stimuli were presented once before repeating again in a new random order.

After study, a quick hurdle test took place, to assess whether participants were paying attention to the pairs and to prepare them for what would be the format of the final test. This quick test also provided a break between study and practice, the longest phases of the experiment. During this hurdle test, participants saw 4 of the previously studied pairs. They were first presented with a word at the top of the screen and asked to think back to the *squiggle* associated with this word. After 4 sec, a question mark appeared below the word, and participants were asked to indicate whether they thought they remembered the correct item (left arrow key) or not (right arrow key). Upon response, three different *squiggles* (all previously studied) appeared below the word, and participants were asked to pick the one that had been paired with that particular word by pressing one of the arrow keys on the

keyboard (left for the leftmost stimulus on the screen, down for the middle stimulus, and right for the rightmost one). This 3-AFC screen disappeared upon participants' response or after 4 sec. The stimuli presented in the hurdle phase were not shown again in the remaining parts of the experiment.

After the hurdle test, participants were informed that they would now have an opportunity to practice some of the pairs. Participants in the restudy condition (24/48) were told they would see some of the previously studied pairs and should use this re-exposure as a chance to encode them again. The pairs were shown in the same way they had during study for 7.5s, and participants had to indicate if they still found it easy or hard to link the pair, using the same response keys as in the study phase. Participants in the retrieval condition (24/48) were asked to actively bring the *squiggles* back to mind, upon being prompted with the word as a retrieval cue. The word appeared at the top of the screen with a question mark below for 5 seconds, during which participants were instructed to vividly bring the *squiggle* back to mind. The corresponding *squiggle* was then presented for 2.5 seconds to provide feedback. In both conditions, 24 of the 36 critical pairs were presented twice for practice. Stimuli were presented in random order, but all 24 items were presented once before repeating again in a new random order. The remaining 12 pairs were not practiced and were used as baseline items to assess memory performance without further practice, and how it evolves with the mere passage of time from the immediate to the delayed test. The assignment of each word-image pair to practice or baseline was counterbalanced across participants. Note that both conditions (retrieval and restudy) were equated for overall practice time and were extremely similar, with the key difference being that participants in the retrieval condition had to consciously bring the correct *squiggle* back to mind whereas the ones in the restudy condition were presented the complete pair.

Pairs were pseudo-randomly allocated to the immediate or delayed test, so that half of all the pairs (12 practiced and 6 baseline) were tested immediately after practice, whereas the other half were tested 7 days later, all in random order. Other than that, the 2 tests were identical and followed the exact same procedure as the hurdle test.

Figure 1. A) General procedure across the four experiments. Participants studied word-object pairs that were then either retrieved or restudied. Experiments 1A and 2A then tested participants' memory for these pairs using a 3-alternative forced choice test, whereas Experiments 1B and 2B employed an associative recognition procedure including remember/know judgments. **B)** Examples of the study materials. The yellow square contains stimuli used in the *squiggles* experiments (Experiments 1A and 1B), whereas the orange square depicts nameable objects as used in Experiments 2A and 2B. **C)** Examples of the perceptual and episodic lures used in Experiments 1B (surrounded by the yellow rectangle) and 2B (orange rectangle).

Statistical analyses

The raw data, as well as the averaged data used in all the analyses throughout the manuscript, are available at <https://osf.io/6zf3t/>. All statistical analyses used practice benefits (accuracy for practiced minus baseline items) as the dependent variable. Since testing effects are typically found after extended delays between practice and final test, we were particularly interested in retrieval benefits at a long delay. Accordingly, in all four experiments of this study, including the present one, we initially conducted one planned comparison, which was a one-tailed independent *t*-test comparing the practice benefits between the retrieval and restudy group on the delayed test.

We were additionally interested in whether there was a shift from a restudy benefit in the immediate test to a retrieval benefit in the delayed test, as previously reported in the testing effect literature (e.g. Roediger & Karpicke, 2006b). To assess this, we ran a 2x2 mixed ANOVA with practice benefit as the dependent variable, and factors practice type (retrieval vs. restudy; manipulated between subjects) and delay (immediate vs. delayed test; manipulated within subjects). Significant effects in this ANOVA were then further assessed in two-tailed post-hoc *t*-tests.

Results

The results of Experiment 1A are depicted in Figure 2A, showing practice effects for the squiggle images depending on type of practice and delay. The one planned comparison of interest revealed no significant benefit of retrieval over restudy on the delayed memory test ($t(46) = -2.44, p = .99$). In fact, a significant effect in the opposite direction was found (see post-hoc tests below).

Results from the mixed ANOVA revealed no significant practice type x delay interaction [$F(1,46) = 1.42, p = .239$]. There was no main effect of delay [$F(1,46) = 1.62, p = .210$], but we did find a significant main effect of practice type [$F(1,46) = 4.08, p = .049, \eta_p^2 = .08$]. Post-hoc comparisons revealed that participants in the restudy group showed significantly larger practice benefits, across immediate and delayed test ($M = 0.12, SD = 0.23$), than those in the retrieval group ($M = 0.03, SD = 0.22; t(94) = -2.14, p = .035$). This restudy advantage was especially evident on the delayed test (immediate test: $t(46) = -.696, p = .490$; delayed test: $t(46) = -2.44, p = .019$).

Figure 2. Practice effects (accuracy for practiced minus baseline pairs) in Experiments 1A (panel **A**) and 1B (panel **B**). Coloured rainclouds represent practice benefits for retrieved items and grey rainclouds practice benefits for restudied items, in an immediate (left of the graph) and delayed (right of the graph) memory test.

Discussion

In Experiment 1A our main comparison of interest revealed no retrieval benefit for novel, meaningless shapes. In contrast, we found a reversal of the testing-effect, with restudied items benefitting significantly more from practice than retrieved items, especially at a longer delay.

There are several possibilities as to why a testing effect was not found here. One is that, as hypothesised, retrieval does not enhance memory for visual stimuli that have no pre-existing associations in memory. In fact, not only was a testing effect not found for these meaningless materials but restudy seemed to benefit their long-term retention to a greater extent. These findings are consistent with theories ascribing testing effects to the co-activation of semantically related information during retrieval (Antony et al., 2017; Carpenter, 2011; Sinclair & Barense, 2019).

An alternative explanation is that retrieval practice for these meaningless shapes was simply too difficult. If participants in the retrieval group were largely unsuccessful at bringing back to mind and visualising the correct items, this could potentially eliminate any practice benefits, and even make

restudy the more advantageous rehearsal strategy. Such failure to retrieve, however, is unlikely to have caused our pattern of results. First, feedback was provided for 2.5s on each retrieval trial, exposing participants to the correct item even if they had not been able to retrieve it. Secondly, performance levels in the immediate and final tests were similar in both conditions (see Table 1). In fact, retrieval practice still led to a benefit at a short delay, albeit smaller than the benefit produced by restudy.

Finally, a third possibility that could account for our results is that the final memory test used in this experiment was not sensitive to retrieval benefits. As Chan and McDermott (2007) have pointed out, testing effects are evident only when the final test specifically encourages controlled retrieval of the studied items. Across four experiments, these authors and others (Pu & Tse, 2014; Verkoeijen et al., 2011) demonstrated that recognition tests that rely heavily on familiarity often do not detect any differences between retrieval and restudy conditions, with differences becoming evident, however, when final memory tests specifically probe recollection.

While previous research suggests that AFC tests may partly depend on recollection (e.g. Kroll, Yonelinas, Dobbins, & Knight, 2000; Kroll, Yonelinas, Dobbins, & Frederick, 2002; Cook, Marsh, & Hicks, 2005), others have argued that discrimination in these tests can be achieved on the basis of familiarity (e.g. Bastin & Van der Linden, 2003).

We therefore conducted the same experiment again, now using a remember/know associative recognition procedure as the final memory test instead of the 3-AFC. Associative recognition tests are thought to depend strongly on recollection (Hockley & Consoli, 1999). This is especially true when participants are asked to judge the oldness of stimuli they are familiar with, but that are presented in a rearranged fashion (e.g. reshuffled study pairs). In this case, familiarity is less useful in supporting recognition (since all of the items are equally familiar; Yonelinas et al., 2010) and the rejection of rearranged pairs requires recollection (Castel & Craik, 2003). However, associative recognition has also been shown to be subject to low-level perceptual influences (Goshen-Gottstein & Moscovitch, 1995). To account for this, we added remember/know judgments to our final test, in order to be able to isolate the recollection component. In this procedure, a ‘remember’ response is thought to reflect recollection processes, whereas ‘know’ responses should be based on familiarity (Migo et al., 2012;

Tulving, 1985), thus allowing us to isolate practice benefits on recollection-based memory specifically.

Experiment 1B

Method

Participants

A novel sample of 48 participants took part in this study. One of the participants failed to show up for session 2, and their data was thus excluded from any further analyses. Participants were randomly assigned to the two experimental conditions. Of the remaining 47 participants ($M_{\text{age}} = 19.1$, $SD = 0.8$, 41 female), 23 performed retrieval practice and 24 restudy practice. Participants were undergraduate or postgraduate students at the University of Birmingham and received either course credits or a monetary reward for their participation. All of them reported normal or corrected-to-normal vision and no history of neurological, psychological or psychiatric condition. Before the start of the experiment, participants signed an informed consent form and at the end of the delayed test were debriefed on the aims of the study. The study was approved by the STEM Ethics Committee of the University of Birmingham.

Materials and procedure

The main difference between Experiments 1A and 1B was the final test, where an associative recognition test including remember/know judgements was used instead of the 3-AFC test. For the associative recognition test, additional *squiggle* images were selected as lure images. Of the 40 *squiggles* shown at study, 20 were knotted (their lines crossed at one point of the drawing) whereas the other 20 were simple *squiggles* (i.e. not knotted – no lines crossed; see yellow square in Figure 1B). This feature was used to select perceptually similar lures for the final test (see below). Other than that, the study phase was the same as in Experiment 1A.

The hurdle test served again as a preparation for the final tests. As before, participants saw the cue word for 4 sec and were asked to think back to the associated *squiggle*. Then, a question mark appeared below, and participants were asked to report by button press whether they remembered the

correct item or not. They were then presented with an item below the word. Participants had to indicate if the item had originally been presented with that same word or not (see below). The item was on screen until response or up to a maximum of 4 sec.

The *squiggle* shown together with a word in the hurdle and the final tests could be i) *exactly* the same that had been studied in the first phase of the experiment (original pairs), ii) a *squiggle* that had never been seen before, but was perceptually similar to the studied one (perceptual lures) or iii) a *squiggle* and a word that had both been previously seen in the experiment, but had not been paired together (episodic lures; see Figure 1C). Knotted squiggles served as perceptual lures for other knotted squiggles as did simple for simple. The participants' task was to decide if a given pairing was old or new. They were made aware of the different types of pairs and were instructed to respond with "old" *only* to the original pairs and "new" to the other two types of pairs (i.e., perceptual and episodic lures). Moreover, if the item was old, they were asked to indicate whether they *remembered* (that is, they distinctively remembered seeing the item and the word paired together during the study phase of the experiment) or *knew* it (had the feeling they had seen the pair before, without precise recollection). Participants pressed the left arrow on the keyboard for "old-remember", the down arrow for "old – know" and the right arrow for "new". These prompts were shown at the bottom of the screen, below the *squiggle*, in the left, middle and right positions, respectively (Figure 1A). In the hurdle phase, 4 original pairs, 1 episodic lure and 1 perceptual lure were shown in random order.

After the hurdle test, participants performed the practice phase twice. Both retrieval and restudy conditions were identical to Experiment 1A. The only difference was that we asked participants in the retrieval condition for a subjective memory response before the *squiggle* appeared on the screen, by pressing the left button if they thought they remembered the correct item and pressing the right button if they did not remember the item. This button press was included to provide us with an indication of memory success, even though subjective. As in the previous experiment, all items were randomly presented once before repeating again, in a new random order. Assignment of each pair to practice or baseline, and of each *squiggle* to target or lure, was counterbalanced across participants.

The final tests (immediate and delayed) followed the same procedure as the hurdle test. Pairs were pseudo-randomly chosen within each participant's learning set to be tested immediately or after a week, so that at each test stage, 18 original pairs, 18 episodic lures and 18 perceptual lures were tested. Of these, 12 were previously practiced items (or lures of practice items) and 6 were baseline items (or lures of baseline items). Half were knotted and half were simple *squiggles*.

Note that in this experiment we used two types of lure items: perceptual and episodic. If retrieval strengthens the meaningful aspects of a memory (Ferreira et al., 2019; Lifanov et al., 2021), this might come at the cost of perceptual detail (Lifanov et al., 2021) and increase false alarms to perceptually similar lures (Lee et al., 2017). For instance, repeatedly retrieving the image of a set of keys (see example in Fig. 1) will presumably activate, and embed the new memory in, the pre-existing knowledge structure related to the concept “key” (Antony et al., 2017). As such the ‘key’ concept would be strengthened, but finer perceptual details of the specific set of keys that had been studied, may be lost. Accordingly, we hypothesised that in our experiments using the associative recognition final memory test, retrieval (compared to restudy) should specifically increase perceptual, but not episodic, false alarms.

Statistical analyses

Our primary metric of interest, in terms of memory performance, was the proportion of original pairs that participants correctly recollected (old-remember responses) after practice compared to no practice. Consistent with the previous experiment, we first ran a targeted one-tailed *t*-test comparing the practice benefits (old-remember responses to practiced – baseline items) in the retrieval and restudy groups on the final delayed test. We then ran a 2x2 mixed ANOVA with factors practice type (retrieval *vs.* restudy; manipulated between subjects) and delay (immediate *vs.* delayed test; manipulated within subjects). Significant results from the ANOVA were further assessed in two-tailed post-hoc comparisons.

Finally, we wanted to analyse false alarm proportions to perceptual and episodic lures. Because participants rarely gave a “remember” response to new pairings, “remember” and “know” false alarms were collapsed for these analyses. We analysed old responses to lures of practiced pairs

minus old responses to lures of baseline items. We were particularly interested if retrieval, compared to restudy, would increase the proportion of perceptual false alarms (Lee et al., 2017).

Results

The results of Experiment 1B are depicted in Figure 2B. The main planned comparison showed no significant retrieval advantage for *squiggles* at the delayed test ($t(45) = -.232, p = 0.59$). Moreover, there was no significant practice x delay interaction [$F(1,45) = .913, p = .344$], nor a main effect of either practice [$F(1,45) = 1.40, p = .243$] or delay [$F(1,45) = 3.09, p = .085$]. No further posthoc tests were thus conducted on the practice benefits.

Analysing false alarm rates, we found no differences in perceptual false alarms (old responses to perceptual lures of practiced – of baseline items) between the retrieval and restudy groups on the delayed test ($t(45) = .926, p = .82$). Additionally, the 2x2 ANOVA indicated no significant interaction between practice type and delay [$F(1,45) = .008, p = .93$], nor a main effect of practice [$F(1,45) = 2.34, p = .133$]. There was, however a main effect of delay [$F(1,45) = 10.67, p = .002$], with participants showing a larger practice-related increase in perceptual false alarms on the delayed test compared to the immediate one ($M_{\text{imm}} = -.097, SD_{\text{imm}} = 0.18; M_{\text{del}} = .034, SD_{\text{del}} = 0.18; t(46) = -3.304, p = .002$). No significant effects were found when analysing using false alarms (old responses to episodic lures of practiced – of baseline items) as the dependent variable for any of the planned analyses (t -test on delayed test: $t(45) = 1.17, p = .88$; delay x practice interaction: $F(1,45) = 1.97, p = .17$; main effect of practice: $F(1,45) = .083, p = .74$; main effect of delay: $F(1,45) = .017, p = .90$).

Table 1: Proportion of correct responses (Experiment 1A) and of correct “old-remember” responses (Experiment 1B) to practiced and baseline *squiggles*, as well as practice effects (practiced-baseline), for each condition across the two experiments using abstract meaningless shapes as stimuli. Mean (standard deviation).

	EXPERIMENT 1A		EXPERIMENT 1B	
	Immediate	Delayed	Immediate	Delayed
	M(SD)	M(SD)	M(SD)	M(SD)
<i>Retrieval</i>				
Practiced	0.83 (0.17)	0.63 (0.21)	0.64 (0.22)	0.37 (0.28)
Baseline	0.76 (0.20)	0.65 (0.18)	0.44 (0.26)	0.21 (0.29)
Practice effects	0.07 (0.05)	-0.02 (0.18)	0.20 (0.21)	0.16 (0.24)
<i>Restudy</i>				
Practiced	0.86 (0.12)	0.66 (0.19)	0.74 (0.20)	0.32 (0.25)
Baseline	0.74 (0.24)	0.54 (0.24)	0.45 (0.27)	0.14 (0.18)
Practice effects	0.12 (0.23)	0.12 (0.24)	0.29 (0.22)	0.18 (0.15)

Discussion

In contrast with Experiment 1A, we did not find a significant reversal of the testing effect in this study although numerically, practice benefits were still higher for the restudy condition (see Table 1). Crucially, we did not find a significant testing-effect either. Together with Experiment 1A, this pattern of results suggests that retrieval does not enhance memory for images that have no pre-existing semantic representation. The finding is congruent with predominant theories of the testing effect suggesting that spreading activation plays a role in retrieval benefits (Antony et al., 2017; Carpenter, 2011; Ritvo et al., 2019; Sinclair & Barense, 2019): novel, meaningless materials can be

assumed to preclude the spread of activation due to a lack of a pre-existing associative network, resulting in no testing effect. Instead, restudy can be beneficial in such situations, allowing for additional exposure to the novel materials.

It should be noted, however, that the null findings from Experiment 1B in themselves do not provide strong evidence for or against any theory. If the lack of pre-existing knowledge explains the absence of a testing effect in our first two experiments, we should expect a change in direction of the practice benefits when the target stimuli have a distinctive (semantic) meaning, with a clear testing effect emerging on the delayed test.

We thus conducted two further experiments, replacing the *squiggles* with concrete nameable objects. In Experiment 2A we used a 3-AFC final memory test, whereas in Experiment 2B participants' memory was probed with an associative recognition test including remember/know judgments, mirroring Experiments 1A and 1B, respectively. We hypothesised that a retrieval-induced enhancement should be especially evident in Experiment 2B, where the memory test specifically probes recollection (Chan & McDermott, 2007; Pu & Tse, 2014; Verkoeijen et al., 2011).

Experiment 2A

Method

Participants

A new sample of 48 participants ($M_{\text{age}} = 19.2$, $SD = 1.13$, 46 female) took part in this study. As in the previous experiments, each participant was randomly assigned to one of the two practice conditions (24 assigned to retrieval and 24 to restudy). Participants were undergraduate or postgraduate students at the University of Birmingham and received either course credits or a monetary reward for their participation. All of them reported normal or corrected-to-normal vision and no history of neurological, psychological or psychiatric condition. Before starting the experiment, participants signed an informed consent form and at the end of the experiment were debriefed on the aims of the study. The study was approved by the STEM Ethics Committee of the University of Birmingham.

Materials and procedure

For this experiment, unique nameable objects were chosen as stimuli to be paired with words. The objects were chosen from the Bank of Standardized Stimuli (BOSS; Brodeur et al., 2014; <https://sites.google.com/site/bosstimuli/>) and modified to greyscale (Figure 1B, pink square).

This experiment followed the same procedure as Experiment 1A. However, to adjust the level of difficulty of the task (nameable objects are easier to remember than abstract shapes, as revealed in a pilot study), in this experiment there was only one study cycle instead of two, and the total number of stimuli was increased. Participants studied a total of 76 word-object pairs. The cue words had similar levels of imageability ($M = 564$, $SD = 8.7$), concreteness ($M = 582.8$, $SD = 28.2$) and meaningfulness ($M = 443.4$, $SD = 31.51$), as in the previous experiments. Four of the 76 words were used in the hurdle phase and not seen again throughout the experiment. From the remaining 72, 48 were used as part of the retrieval/restudy pairs, and 24 in baseline pairs. As in the previous experiments, the assignment of each pair to item type (practiced or baseline) was counterbalanced across participants. Pairs were pseudo-randomly assigned to the immediate or delayed test, so that each final test, immediate and delayed, assessed memory for 24 of the practised items and for 12 of the baseline ones.

Statistical analyses

Statistical analyses were conducted in the same fashion as Experiment 1A: we first conducted a one-tailed independent t -test, comparing practice benefits (practiced – baseline) for retrieval vs restudy on the delayed test, where testing effects are typically observed. We then computed a 2x2 mixed ANOVA on practice benefits, with factors practice type (retrieval vs. restudy; manipulated between subjects) and delay (immediate vs. delayed test; manipulated within subjects). Significant results from the ANOVA were further assessed in two-tailed post-hoc t -tests.

Results

The results of Experiment 2A are depicted in Figure 3A. The planned comparison of practice benefits on the delayed test showed no significant retrieval advantage ($t(46) = 1.11$, $p = .136$).

We found, however, a significant practice x delay interaction [$F(1,46) = 4.71, p = .035, \eta_p^2 = .09$]. In the immediate test, participants in the restudy condition showed larger practice effects ($M = 0.17, SD = 0.13$) than those in the retrieval condition ($M = 0.11, SD = 0.16$), and this pattern was numerically reversed on the delayed test ($M_{\text{restudy}} = 0.14, SD_{\text{restudy}} = 0.14$; $M_{\text{retrieval}} = 0.18, SD_{\text{retrieval}} = 0.14$). Post-hoc comparisons between groups did, however, not reach statistical significance (immediate test: $t(46) = -1.48, p = .15$; see planned comparison for delayed test). Additionally, there was no significant main effect of practice [$F(1,46) = .056, p = .814$], nor a significant main effect of delay [$F(1,46) = .531, p = .470$].

Figure 3. Practice effects (accuracy for practiced minus baseline pairs) in Experiments 2A (panel **A**) and 2B (panel **B**). Coloured rainclouds represent practice benefits for retrieved items and grey rainclouds practice benefits for restudied items, in an immediate (left of the graph) and delayed (right of the graph) memory test.

Discussion

In this experiment we found a pattern of results that qualitatively matches the one commonly reported in the testing effect literature (Roediger & Karpicke, 2006b): while restudy led to numerically larger benefits than retrieval in the immediate test, this pattern was reversed in the delayed test, as indicated by a significant group-by-delay interaction. Although these results are in line with a testing effect for nameable objects, they should be interpreted with caution, since when comparing the two conditions directly in post-hoc tests, neither the restudy advantage on the immediate test, nor the retrieval advantage on the delayed test, were statistically robust.

It is possible that retrieval simply does not enhance memory for visual stimuli, even when they do have a distinctive meaning. This seems unlikely, however, given that a number of previous studies have reported a testing effect for meaningful visual materials (Carpenter & Kelly, 2012; Carpenter & Pashler, 2007; Guran et al., 2019; Herweg et al., 2018). We therefore added a fourth experiment, again using meaningful object images, but probing memory with an associative recognition test with a remember/know procedure, which we used to isolate the recollective component that presumably benefits most strongly from retrieval practice (Chan & McDermott, 2007; Pu & Tse, 2014; Verkoeijen et al., 2011).

Experiment 2B

Method

Participants

Another 48 participants took part in this study. Due to data loss during digitization, demographic data is only available for half of the sample. For the participants whose demographic data are available, mean age was 21.6 years old ($SD = 3.6$; 22 out of 24 female). As in the previous experiments, participants were randomly assigned to a retrieval or a restudy condition (24 participants per condition). All participants were undergraduate or postgraduate students at the University of Birmingham and received either course credits or a monetary reward for their participation. All of them reported normal or corrected-to-normal vision and no history of neurological or psychiatric conditions. Previous to the start of the experiment, participants signed an informed consent form and

at the end of the delayed test were debriefed on the aims of the study. The study was approved by the STEM Ethics Committee of the University of Birmingham.

Materials and procedure

The same materials from Experiment 2A were used in Experiment 2B. This experiment followed a similar procedure as that of Experiment 1B, the only differences being the number of study cycles (only one instead of two) and the number of stimuli. The same number of stimuli as in Experiment 2A was used (72 critical objects), with additional lures added to this image pool. Episodic lures were images that had been learned and practiced throughout the experiment but were paired with a different word during the final test (i.e., re-combined pairs). Perceptual lures were new, unstudied images that resembled the practiced item (see Figure 1C). Many of these images were chosen through Google image searches, as not every stimulus used in Experiment 2A had a perceptually similar image in the BOSS database. Pair assignment to item type (practice or baseline) was counterbalanced across participants, as was the assignment of each image to target or lure. Pairs were pseudo-randomly assigned to the immediate or delayed test, so that each final memory test (immediate and delayed) probed the 36 original pairs, 36 perceptual lures and 36 episodic lures, of which 24 were practiced items and 12 baseline items.

Statistical analyses

Statistical analyses were conducted in the same way as Experiment 1B: we first conducted a single independent *t*-test on the practice benefits for original pairs (old-remember responses to practiced original pairs – old-remember responses to baseline original pairs). This planned comparison was followed up by a 2x2 mixed ANOVA with factors practice type (retrieval *vs.* restudy; manipulated between subjects) and delay (immediate *vs.* delayed test; manipulated within subjects). Significant results from the ANOVA were followed up with two-tailed post-hoc tests.

Finally, we analysed false alarms to perceptual and episodic lures by subtracting all old responses (remember and know) to lures of baseline items from old responses to lures of practiced items.

Results

The results of Experiment 2B are depicted in Figure 3B. Our main comparison of interest yielded a significant benefit of retrieval practice for the nameable objects on the delayed test ($t(46) = 2.02, p = .025$). Furthermore, the 2x2 ANOVA revealed a significant interaction between practice and delay [$F(1,46) = 6.35, p = .015, \eta_p^2 = .12$] and a significant main effect of delay [$F(1,46) = 11.66, p = .001, \eta_p^2 = .20$], but no main effect of practice [$F(1,46) = 0.48, p = .828$]. Posthoc t -tests further revealed that participants in the restudy condition performed marginally better ($M = 0.31, SD = 0.22$) than those in the retrieval condition ($M = 0.20, SD = 0.21$) on the immediate test ($t(46) = -1.79, p = .08$) and that this pattern was reversed on the delayed test ($M_{\text{restudy}} = 0.35, SD_{\text{restudy}} = 0.16; M_{\text{retrieval}} = 0.44, SD_{\text{retrieval}} = 0.16$; see planned comparison). Post-hoc tests, following up on the main effect of delay, showed that practice benefits were particularly evident on the delayed test, compared to the immediate test ($M_{\text{immediate}} = 0.26, SD_{\text{immediate}} = 0.22; M_{\text{delayed}} = 0.40, SD_{\text{delayed}} = 0.17; t(47) = -3.24, p = .002$).

Finally, when analysing false alarm rates (old responses to lures of practiced – of baseline items), our planned t -test revealed no significant difference in perceptual false alarms (old responses to perceptual lures of practiced – of baseline items) between the retrieval and restudy group on the delayed test ($t(46) = .026, p = .49$). There was also no significant practice x delay interaction [$F(1,46) = .181, p = .67$] or main effect of practice [$F(1,46) = .132, p = .72$]. Like in Experiment 1B, there was a significant main effect of delay [$F(1,46) = 14.01, p < .001, \eta_p^2 = .23$], evidencing that practice increased the proportion of perceptual false alarms on the delayed test ($M = 0.09, SD = 0.17$) relative to the immediate test ($M = -0.04, SD = 0.19; t(46) = -3.78, p < .001$), however, this effect was not specific to retrieval practice. Analyses on episodic false alarms (old responses to episodic lures of practiced – of baseline items), revealed no significant results (t -test on delayed test: $t(46) = -.65, p = .26$; delay x practice interaction: $F(1,46) = 1.66, p = .20$; main effect of practice: $F(1,46) = .097, p = .76$; main effect of delay: $F(1,45) = .031, p = .86$).

Table 2: Proportion of correct responses (Experiment 2A) and of correct “old-remember” responses (Experiment 2B) to practiced and baseline object images, as well as practice effects (practiced-baseline), for each condition across the two experiments using concrete nameable objects as stimuli. Mean (standard deviation).

	EXPERIMENT 2A		EXPERIMENT 2B	
	Immediate	Delayed	Immediate	Delayed
	M(SD)	M(SD)	M(SD)	M(SD)
<i>Retrieval</i>				
Practiced	0.87 (0.11)	0.54 (0.19)	0.81 (0.20)	0.57 (0.20)
Baseline	0.76 (0.20)	0.36 (0.18)	0.61 (0.23)	0.13 (0.11)
Practice effects	0.11 (0.16)	0.18 (0.14)	0.20 (0.21)	0.44 (0.16)
<i>Restudy</i>				
Practiced	0.92 (0.08)	0.57 (0.16)	0.89 (0.11)	0.51 (0.20)
Baseline	0.75 (0.16)	0.43 (0.18)	0.58 (0.24)	0.16 (0.14)
Practice effects	0.17 (0.13)	0.14 (0.14)	0.31 (0.22)	0.35 (0.16)

Discussion

Using concrete nameable objects and a test where we isolate recollection-based responses, we now find the expected significant retrieval advantage at long delays, as typically reported in the testing effect literature (Coppens et al., 2011; Roediger & Karpicke, 2006b; Toppino & Cohen, 2009; van den Broek et al., 2014). Consistent with previous experiments, we also find that while restudy has an advantage at short delays, having engaged in retrieval during the practice phase entails a larger benefit when memory is tested after long delays. Thus, retrieval seems to enhance retention of visual stimuli but only when they can be attributed a unique meaning.

For this and Experiment 1B we had additionally hypothesised that retrieval would lead to an increase in perceptual false alarms. Across both experiments, practice led to an increase over time of perceptual, but not episodic, false alarms as evidenced by the main effect of delay when analysing old responses to lures of practiced items minus old responses to lures of baseline items. At the delayed test, participants did commit more false alarms when judging perceptual lures (old responses to lures of practiced – of baseline items) compared to episodic lures after a delay, in line with Lee et al. (2017). However, contrary to our hypothesis, this difference was not retrieval-specific, as perceptual false alarms in the delayed test did not differ between the retrieval and the restudy groups. In this study, therefore, retrieval-mediated learning did not specifically impair the retention of perceptual detail of the practiced images.

General discussion

We here investigated whether the testing effect extends to visual materials. Across four experiments, we varied the type of material (meaningless and meaningful visual images), and the format of the final memory test (3-AFC and remember/know recognition tests). Within each experiment, one group of participants practiced by retrieval and the other by restudy, and we measured the resulting practice benefits immediately after practice and following a one-week delay. Our results show that retrieval practice does not enhance memory for abstract, non-meaningful shapes irrespective of the final test format. Such material instead benefits from initial restudy, a visual type of practice. This restudy advantage was most pronounced in Experiment 1A using an alternative forced-choice memory test, suggesting that novel images with no pre-existing meaning benefit from visual re-exposure, specifically on rather visually driven memory tests. This pattern reversed for associations that involved images of meaningful everyday objects: while restudy was still the more beneficial practice strategy when followed by a test immediately, retrieval outperformed restudy after a longer delay, in particular in Experiment 2B where we specifically probed recollection. The latter finding of a delayed retrieval advantage mirrors many studies reported in the literature using verbal materials (Roediger & Karpicke, 2016a; Rowland, 2014).

Although previous work has shown a testing effect for visual materials, it is important to emphasize that most of these studies tested participants' memory for words or names associated with a visual stimulus, rather than its visual features (e.g., Carpenter & DeLosh, 2005; Coppens et al., 2011; Jonker et al., 2018). Furthermore, those studies that did test the retention of the visual elements of the images often used materials that can easily be verbalised (Carpenter & Kelly, 2012; Carpenter & Pashler, 2007; Guran et al., 2019; Herweg et al., 2018). As such, it is hard to distinguish if retrieval practice in these experiments enhanced the perceptual or semantic features of the stimuli (but see Lifanov et al., 2021).

A study by Kang (2010) constitutes a notable exception, reporting a testing effect for difficult-to-verbalise visual stimuli. In this study, participants learned English words paired with their corresponding Chinese characters. The characters were then restudied or retrieved (visually imagined) and, in a final memory test, participants were asked to draw the Chinese character associated with each English word. Kang found a significant testing effect across three experiments, in contrast with our *squiggles* experiments (Experiments 1A and 1B). However, when Kang asked participants to describe the strategies they used to perform the task (Experiment 3), 64% of strategy descriptions were classified as verbal, and the use of a verbal strategy was associated with better recall in both practice conditions. Thus, it seems that retrieval benefits in Kang's experiments might have relied on the verbalisation of stimuli, rather than the enhancement of their visual features.

Two other studies tested visual aspects of the practiced stimuli. In a study by Sutterer and Awh (2016), participants learned nameable objects with different colours and were asked to reconstruct the original colour on a colour wheel, after an intervening retrieval or restudy condition. Across three experiments, these authors showed that retrieval practice, compared to restudy, increased the future probability of successful item access (i.e. a testing effect), but did not enhance the precision of the recalled memories (though see Schuetze et al., 2019). Another recent study by Lifanov and colleagues (2021) showed that repeated retrieval of visual object memories strengthens their conceptual features more than their perceptual ones. This semantic advantage was especially evident after a 2-day delay, and significantly smaller in a restudy group. Both studies thus suggest that

repeated retrieval after learning improves future access to the concept represented by a visual image, but not necessarily its surface perceptual features.

Going beyond this previous work, our findings indicate that retrieval-induced strengthening emerges on the basis of meaning, and that stimuli with no inherent meaning, which cannot be linked to pre-existing associated knowledge, do not benefit from testing in the same way. This idea is in fact highly congruent with several cognitive theories of the testing effect, which all make the common assumption that retrieval benefits stem from a more conceptual-type processing during retrieval than during restudy. Based on the fuzzy trace theory (Brainerd et al., 2008; Brainerd & Reyna, 2004; Reyna & Brainerd, 1995), Verkoeijen and colleagues (2012) suggested that visual re-exposure during restudy causes strengthening of surface features. In contrast, participants use semantic cues to recover mnemonic information during retrieval practice, consequently strengthening the semantic features of the memory trace. In line with this theory, we found that abstract shapes that carry no inherent meaningful information, and cannot be linked to pre-existing knowledge, do not benefit from testing, presumably due to a lack of semantic re-processing. A type of practice that enhances surface (perceptual) features is thus more beneficial for their long-term retention. On the other hand, when meaning is available and stimuli can be processed semantically, retrieval leads to better long-term retention.

Along similar lines, other authors (Congleton & Rajaram, 2011, 2012; Zaromb & Roediger, 2010) suggested that restudy enhances item-specific processing, while testing enhances relational processing. Using categorised lists, Congleton and Rajaram (2012) showed that, compared to restudy, retrieval enhances the semantic organisation of materials. The authors used Adjusted Ratio of Clustering (ARC; Roenker et al., 1971) scores to determine the strength of retrieval organisation, by quantifying the degree to which participants cluster items from the same category at retrieval. The ARC scores showed that i) conceptually related information within a given stimulus set is grouped more cohesively during retrieval; and ii) this clustering endures over time. With respect to our own results, retrieval advantages could thus arise from enhanced semantic organisation during retrieval, and no such advantages will appear for meaningless materials that cannot be organised in taxonomic categories.

These theories of the testing effect, while well in line with our findings, do not offer a satisfying explanation of the mechanisms by which retrieval strengthens semantic over perceptual stimulus features. A possible explanation is offered by elaborative retrieval theories, which suggest that retrieval benefits depend on the reactivation of semantically related information during retrieval. This co-active information can then be used as an additional retrieval cue (Carpenter, 2009) or as mediating information that links the cue and target (Carpenter, 2011; Pyc & Rawson, 2010). The key difference between retrieval and restudy, in this framework, is that retrieval allows for related information to be co-active (and become integrated) with the target, whereas activation during restudy is largely limited to the target item itself (Antony et al., 2017; Carpenter & Yeung, 2017; Sinclair & Barense, 2019).

Evidence for the role of spreading activation during retrieval (vs. restudy) comes from both neuroimaging (Ferreira et al., 2019; Jonker et al., 2018) and behavioural (Akan et al., 2018; Chan, 2010; McDermott, 2006) studies. False memory studies, for instance, have shown that tests can increase the occurrence of false memories for semantically related lures, when the studied lists share a common semantic theme (McDermott, 2006). Moreover, several experiments have now shown that testing strengthens memory not only for the retrieved target items, but also for semantically related material encoded during initial learning, an effect termed retrieval-induced facilitation – or RIFA (Chan, 2010). RIFA is assumed to occur because people actively search for related information when attempting to retrieve the target. Critically, this effect depends on the degree to which items can be integrated – if the stimuli do not allow for integration, testing harms the retention of semantically related information, and retrieval-induced forgetting occurs instead. As an important note, although we here focus on the reactivation of semantically related items, similar principles should apply to episodically related information, as there is evidence that retrieval can also strengthen co-activated contextual associations (Akan et al., 2018; Jonker et al., 2018).

A large body of evidence thus supports the central role of relational knowledge in retrieval-induced memory strengthening. The role that previous knowledge plays in enhancing memory retention has long been established: new information is better learned and retained if it can be integrated or contrasted with a pre-existing schema (Bonasia et al., 2018; Greve et al., 2019;

Schlichting et al., 2015; van Kesteren et al., 2012, 2013; Zeithamova et al., 2012). Our present data suggest that the existence of previous knowledge is a necessary condition for the testing effect to emerge. As far as we are aware, the role of previous knowledge on the testing effect has not been investigated explicitly in previous work. Studies on sleep-dependent memory enhancement do offer some evidence, however, that pre-existing knowledge is indeed necessary for memories to become consolidated.

In sleep studies, target information is often paired with a sound or smell during learning, that can then be used as a cue to reactivate a memory during sleep. Such Targeted Memory Reactivation studies (TMR) typically show that information that was cued during sleep is recalled better in a final memory test than non-cued information (Rasch et al., 2007; Rudoy et al., 2009), and this memory benefit has been attributed to the enforced replay of the cued memories during sleep (e.g. Groch et al., 2017; Schapiro et al., 2017). In a striking parallel with the testing effect, the beneficial effects of TMR disappear if cue and target are presented together during sleep (similar to a restudy condition; Schreiner et al., 2018). Moreover, the memory-enhancing effects of TMR are abolished for novel but not familiar images (Groch et al., 2017), again pointing to a crucial role of previous knowledge in reactivation-induced memory stabilization. These findings also corroborate the notion that wake retrieval and offline reactivation share a common strengthening mechanism (Antony et al., 2017).

In addition to the lack of a testing effect for meaningless materials, a second important finding emerged from our study: even for meaningful objects, we only found a significant testing effect when probing recollection. These results are in line with previous studies showing that retrieval boosts recollection, while leaving familiarity largely unaffected (Chan & McDermott, 2007; Pu & Tse, 2014; Verkoijen et al., 2011). The study by Verkoijen et al (2011) is particularly interesting in this respect, showing that recognition decisions for previously restudied items were more familiarity-based than for previously tested ones, in addition to the recollection boost from retrieving over restudying. Recollection has been shown to reflect a more conceptual-elaborative process, while familiarity reflects a more sensory or perceptual process. For example, recollection benefits more from semantic (*vs* perceptual) encoding than familiarity, whereas perceptual manipulations enhance familiarity more than recollection (see Yonelinas, 2002 for a discussion on this topic). Research on

the levels of processing (Craik & Lockhart, 1972) has robustly shown that deeply encoded items are better remembered, suggesting that semantic encoding specifically enhances recollection-based memory. Using a remember/know paradigm, Gardiner (1988) showed that a semantic compared to a phonemic encoding task led to an increase in “remember” responses, while not changing the ratio of “know” responses. Several further studies using the same paradigm have confirmed this observation (e.g. Bisby et al., 2010; Bodner & Lindsay, 2003; d’Ydewalle & Van Damme, 2007; Gardiner et al., 1996; Java et al., 1997). According to Anderson (2020), these deep processing advantages stem from the integration of new experiences with previously stored memories. This assumption resonates well with our own findings showing the importance of previous knowledge for retrieval-induced strengthening, and the absence of a testing effect when probing memory with a more visually-driven alternative forced choice test.

A third noteworthy observation in our study was that for meaningful materials, we only found a robust testing effect after a long delay between practice and the final test. Delayed retrieval benefits are common in the testing effect literature (Coppens et al., 2011; Roediger & Karpicke, 2006b; Toppino & Cohen, 2009; van den Broek et al., 2014) and show that the behavioural benefits of retrieval evolve slowly, and are often found only after longer delays. Roediger & Karpicke (2006b), for instance, found that in an immediate test, participants performed better after studying prose passages twice than after studying and retrieving them. This pattern was reversed after two days, and after a week the study plus test condition strongly outperformed studying the passages twice. Some of the theories discussed above offer an explanation for this practice by delay interaction, also observed here in Experiment 2B. Congleton and Rajaram (2012) posit that while retrieval and restudy both engage relational and item-specific processing, retrieval favours the former and restudy the latter. This combination of relational and item-specific processing can lead to a restudy advantage at a short delay. Critically, however, the relational processing induced by restudy is fragile and transient, and thus less effective in preventing items from being forgotten over time. In contrast, retrieval creates a more robust and stable organisation across time, leading to a retrieval advantage at long delays. The semantic mediator hypothesis explains long-term retrieval advantages based on literature suggesting that long-term memory is semantic in nature (e.g. Bartlett, 1932), in contrast with a more perceptual

nature of short-term memory (Baddeley, 1976). If retrieval is beneficial because it activates semantically related information, as posited by this hypothesis, then the advantages of retrieval would be more evident on a delayed final test, which is more sensitive to semantic processing than an immediate test (Carpenter, 2011).

These cognitive theories are complemented by neurobiologically and computationally inspired accounts of retrieval practice effects. The nonmonotonic plasticity hypothesis (Detre et al., 2013; Newman & Norman, 2010) posits that strong co-activation leads to the strengthening of connections and thus integration between memories (Ritvo et al., 2019). Due to the imprecise nature of retrieval, this co-activation of memories is more likely to occur during testing than during restudy, where only the target pattern should be reimposed (Antony et al., 2017; Carpenter, 2009; Sinclair & Barense, 2019). In neurobiological terms, retrieval will trigger hippocampal replay and an enhanced communication with neocortex (see Wing et al., 2013 for neuroimaging evidence), allowing for the integration of the target memory with pre-existing neocortical knowledge structures (Antony et al., 2017; Ferreira et al., 2019). At a short delay, it is assumed that participants rely less on this additional neocortical representation, because the relatively strong hippocampal memory trace can sufficiently support recall, leading to equivalent restudy and retrieval benefits. At long delays, however, the hippocampal trace will be less accessible (e.g. due to decay, interference or context shifts; Frankland & Bontempi, 2005; Hardt et al., 2013; Richards & Frankland, 2017; Sadeh et al., 2014, 2016), such that memory recall depends more heavily on additional access routes via neocortex. Delayed memory tests thus make the strengthening induced by repeated retrieval practice more visible.

In summary, we show across four behavioural experiments that testing effects for visual stimuli rely on existing knowledge and are most robustly found when probing the recollective component of memory at long delays. Novel, meaningless shapes instead benefit from repeated learning and visual exposure, especially on a more visually driven final memory test. Together, our findings inform cognitive and neurobiologically inspired theories of the testing effect, supporting those that place an emphasis on the role of spreading activation during retrieval. They also have important implications for educational contexts, showing that rehearsal strategies should be adapted according to the type of to-be-remembered material.

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Author note:

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The authors declare no conflicts of interest.

References

- Anderson, M.C. (2020). Episodic Memory: Organizing and remembering. In Baddeley, A., Eisenck, M.W. and Anderson, M.C. (Eds.), *Memory* (pp.175). Oxon: Routledge.
- Akan, M., Stanley, S. E., & Benjamin, A. S. (2018). Testing enhances memory for context. *Journal of Memory and Language*, 103(January), 19–27. <https://doi.org/10.1016/j.jml.2018.07.003>
- Antony, J. W., Ferreira, C. S., Norman, K. A., & Wimber, M. (2017). Retrieval as a Fast Route to Memory Consolidation. *Trends in Cognitive Sciences*, 21(8), 573–576. <https://doi.org/10.1016/j.tics.2017.05.001>
- Bastin, C., & Van der Linden, M. V. (2003). The contribution of recollection and familiarity to recognition memory: A study of the effects of test format and aging. *Neuropsychology*. <https://doi.org/10.1037/0894-4105.17.1.14>
- Bisby, J. A., Leitz, J. R., Morgan, C. J. A., & Curran, H. V. (2010). Decreases in recollective experience following acute alcohol: A dose-response study. *Psychopharmacology*, 208(1), 67–74. <https://doi.org/10.1007/s00213-009-1709-y>
- Bodner, G. E., & Lindsay, D. S. (2003). Remembering and knowing in context. In *Journal of Memory and Language* (Vol. 48, Issue 3, pp. 563–580). Academic Press Inc. [https://doi.org/10.1016/S0749-596X\(02\)00502-8](https://doi.org/10.1016/S0749-596X(02)00502-8)
- Brainerd, C. J., & Reyna, V. F. (2004). Fuzzy-trace theory and memory development. *Developmental Review*, 24(4), 396–439. <https://doi.org/10.1016/j.dr.2004.08.005>
- Brainerd, C. J., Reyna, V. F., & Ceci, S. J. (2008). Developmental Reversals in False Memory: A Review of Data and Theory. *Psychological Bulletin*, 134(3), 343–382. <https://doi.org/10.1037/0033-2909.134.3.343>
- Brodeur, M. B., Guérard, K., & Bouras, M. (2014). Bank of Standardized Stimuli (BOSS) Phase II: 930 New Normative Photos. *PLoS ONE*, 9(9), e106953. <https://doi.org/10.1371/journal.pone.0106953>
- Carpenter, S. K. (2009). Cue strength as a moderator of the testing effect: The benefits of elaborative retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(6), 1563–1569. <https://doi.org/10.1037/a0017021>

- Carpenter, S. K. (2011). Semantic Information Activated During Retrieval Contributes to Later Retention: Support for the Mediator Effectiveness Hypothesis of the Testing Effect. *Journal of Experimental Psychology: Learning Memory and Cognition*, 37(6), 1547–1552.
<https://doi.org/10.1037/a0024140>
- Carpenter, S. K., & DeLosh, E. L. (2005). Application of the testing and spacing effects to name learning. *Applied Cognitive Psychology*, 19(5), 619–636. <https://doi.org/10.1002/acp.1101>
- Carpenter, S. K., & Kelly, J. W. (2012). Tests enhance retention and transfer of spatial learning. *Psychonomic Bulletin and Review*, 19(3), 443–448. <https://doi.org/10.3758/s13423-012-0221-2>
- Carpenter, S. K., & Pashler, H. (2007). Testing beyond words: Using tests to enhance visuospatial map learning. *Psychonomic Bulletin & Review*, 14(3), 474–478.
<https://doi.org/10.3758/BF03194092>
- Carpenter, S. K., & Yeung, K. L. (2017). The role of mediator strength in learning from retrieval. *Journal of Memory and Language*, 92, 128–141. <https://doi.org/10.1016/j.jml.2016.06.008>
- Chan, J. C. K. (2010). Long-term effects of testing on the recall of nontested materials. *Memory*, 18(1), 49–57. <https://doi.org/10.1080/09658210903405737>
- Chan, J. C. K., & McDermott, K. B. (2007). The testing effect in recognition memory: A dual process account. *Journal of Experimental Psychology: Learning Memory and Cognition*, 33(2), 431–437. <https://doi.org/10.1037/0278-7393.33.2.431>
- Congleton, A. R., & Rajaram, S. (2011). The Influence of Learning Methods on Collaboration: Prior Repeated Retrieval Enhances Retrieval Organization, Abolishes Collaborative Inhibition, and Promotes Post-Collaborative Memory. *JEP:General*, 140(4), 535–51.
<https://doi.org/10.1037/a0024308>
- Congleton, A., & Rajaram, S. (2012). The origin of the interaction between learning method and delay in the testing effect: The roles of processing and conceptual retrieval organization. *Memory and Cognition*, 40(4), 528–539. <https://doi.org/10.3758/s13421-011-0168-y>
- Coppens, L. C., Verkoeijen, P. P. J. L., & Rikers, R. M. J. P. (2011). Learning Adinkra symbols: The effect of testing. *Journal of Cognitive Psychology*, 23(3), 351–357.
<https://doi.org/10.1080/20445911.2011.507188>

- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11(6), 671–684.
[https://doi.org/10.1016/S0022-5371\(72\)80001-X](https://doi.org/10.1016/S0022-5371(72)80001-X)
- d'Ydewalle, G., & Van Damme, I. (2007). Memory and the Korsakoff syndrome: Not remembering what is remembered. *Neuropsychologia*, 45(5), 905–920.
<https://doi.org/10.1016/j.neuropsychologia.2006.08.025>
- Detre, G. J., Natarajan, A., Gershman, S. J., & Norman, K. A. (2013). Moderate levels of activation lead to forgetting in the think/no-think paradigm. *Neuropsychologia*, 51(12), 2371–2388.
<https://doi.org/10.1016/j.neuropsychologia.2013.02.017>
- Ferreira, C. S., Charest, I., & Wimber, M. (2019). Retrieval aids the creation of a generalised memory trace and strengthens episode-unique information. *NeuroImage*, 201(July), 115996.
<https://doi.org/10.1016/j.neuroimage.2019.07.009>
- Frankland, P. W., & Bontempi, B. (2005). The organization of recent and remote memories. *Nature Reviews Neuroscience*, 6(2), 119–130. <https://doi.org/10.1038/nrn1607>
- Gardiner, J. M. (1988). Functional aspects of recollective experience. *Memory & Cognition*, 16(4), 309–313. <https://doi.org/10.3758/BF03197041>
- Gardiner, J. M., Java, R. I., & Richardson-Klavehn, A. (1996). How Level of Processing Really Influences Awareness in Recognition Memory. *Canadian Journal of Experimental Psychology*, 50(1), 114–122. <https://doi.org/10.1037/1196-1961.50.1.114>
- Goshen-Gottstein, Y., & Moscovitch, M. (1995). Repetition Priming Effects for Newly Formed Associations Are Perceptually Based: Evidence From Shallow Encoding and Format Specificity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21(5), 1249–1262.
<https://doi.org/10.1037/0278-7393.21.5.1249>
- Groch, S., Schreiner, T., Rasch, B., Huber, R., & Wilhelm, I. (2017). Prior knowledge is essential for the beneficial effect of targeted memory reactivation during sleep. *Scientific Reports*, 7, 1–7.
<https://doi.org/10.1038/srep39763>
- Groh-Bordin, C., Zimmer, H. D., & Ecker, U. K. H. (2006). Has the butcher on the bus dyed his hair? When color changes modulate ERP correlates of familiarity and recollection. *NeuroImage*,

- 32(4), 1879–1890. <https://doi.org/10.1016/j.neuroimage.2006.04.215>
- Guran, C.-N. A., Herweg, N. A., & Bunzeck, X. (2019). Age-Related Decreases in the Retrieval Practice Effect Directly Relate to Changes in Alpha-Beta Oscillations. *Journal of Neuroscience*, 39(22) 4344–4352. <https://doi.org/10.1523/JNEUROSCI.2791-18.2019>
- Hardt, O., Nader, K., & Nadel, L. (2013). Decay happens: The role of active forgetting in memory. *Trends in Cognitive Sciences*, 17(3), 111–120. <https://doi.org/10.1016/j.tics.2013.01.001>
- Herweg, N. A., Sommer, T., & Bunzeck, N. (2018). Retrieval demands adaptively change striatal old/new signals and boost subsequent long-term memory. *Journal of Neuroscience*, 38(3), 745–754. <https://doi.org/10.1523/JNEUROSCI.1315-17.2017>
- Hockley, E., & Consoli, A. (1999). Familiarity and recollection in item and associative recognition. In *Memory & Cognition* (Vol. 27, Issue 4).
- Java, R. I., Gregg, V. H., & Gardiner, J. M. (1997). What Do People Actually Remember (and Know) in “Remember/Know” Experiments? *European Journal of Cognitive Psychology*, 9(2), 187–197. <https://doi.org/10.1080/713752553>
- Jonker, T. R., Dimsdale-Zucker, H., Ritchey, M., Clarke, A., & Ranganath, C. (2018). Neural reactivation in parietal cortex enhances memory for episodically linked information. *Proceedings of the National Academy of Sciences of the United States of America*, 115(43), 11084–11089. <https://doi.org/10.1073/pnas.1800006115>
- Kang, S. H. K. (2010). Enhancing visuospatial learning: The benefit of retrieval practice. *Memory and Cognition*, 38(8), 1009–1017. <https://doi.org/10.3758/MC.38.8.1009>
- Karpicke, J. D., Lafayette, W., & States, U. (2017). Retrieval-Based Learning : A Decade of Progress. In *Learning and Memory: A Comprehensive Reference* (Third Edit). Elsevier. <https://doi.org/10.1016/B978-0-12-805159-7.02023-4>
- Lee, H., Samide, R., Richter, F. R., & Kuhl, B. A. (2017). *Decomposing parietal memory reactivation to predict consequences of remembering*. <https://doi.org/10.1101/208678>
- Lifanov, J., Linde-Domingo, J., & Wimber, M. (2021). Feature-specific reaction times reveal a semanticisation of memories over time and with repeated remembering. *Nature Communications* 2021 12:1, 12(1), 1–10. <https://doi.org/10.1038/s41467-021-23288-5>

- Mcdermott, K. B. (2006). Paradoxical effects of testing: Repeated retrieval attempts enhance the likelihood of later accurate and false recall. In *Memory & Cognition* (Vol. 34, Issue 2).
- Migo, E. M., Mayes, A. R., & Montaldi, D. (2012). Measuring recollection and familiarity: Improving the remember/know procedure. In *Consciousness and Cognition* (Vol. 21, Issue 3, pp. 1435–1455). Academic Press. <https://doi.org/10.1016/j.concog.2012.04.014>
- Newman, E. L., & Norman, K. A. (2010). Moderate Excitation Leads to Weakening of Perceptual Representations. *Cerebral Cortex*, 20, 2760–2770. <https://doi.org/10.1093/cercor/bhq021>
- Pu, X., & Tse, C. S. (2014). The influence of intentional versus incidental retrieval practices on the role of recollection in test-enhanced learning. *Cognitive Processing*, 15(1), 55–64. <https://doi.org/10.1007/s10339-013-0580-2>
- Pyc, M. A., & Rawson, K. A. (2010). Why testing improves memory: mediator effectiveness hypothesis. *Science*, 330(6002), 335. <https://doi.org/10.1126/science.1191465>
- Rasch, B., Büchel, C., Gais, S., & Born, J. (2007). Odor Cues During Slow-Wave Sleep Prompt Declarative Memory Consolidation. *Science*, 315(5817), 1423–1426. <https://doi.org/10.1126/science.1134457>
- Reyna, V. F., & Brainerd, C. J. (1995). Fuzzy-trace theory: An interim synthesis. *Learning and Individual Differences*, 7(1), 1–75. [https://doi.org/10.1016/1041-6080\(95\)90031-4](https://doi.org/10.1016/1041-6080(95)90031-4)
- Richards, B. A., & Frankland, P. W. (2017). The Persistence and Transience of Memory. *Neuron*, 94(6), 1071–1084. <https://doi.org/10.1016/J.NEURON.2017.04.037>
- Ritvo, V. J. H., Turk-Browne, N. B., & Norman, K. A. (2019). Nonmonotonic Plasticity: How Memory Retrieval Drives Learning. In *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2019.06.007>
- Roediger, H. L., & Karpicke, J. D. (2006a). The Power of Testing Memory Basic Research and Implications for Educational Practice. *Perspectives on Psychological Science*, 1(3), 181–210. <http://journals.sagepub.com/doi/pdf/10.1111/j.1745-6916.2006.00012.x>
- Roediger, H. L., & Karpicke, J. D. (2006b). Test-Enhanced Learning Taking Memory Tests Improves Long-Term Retention. *Psychological Science*, 17(3), 249–255. <http://journals.sagepub.com/doi/pdf/10.1111/j.1467-9280.2006.01693.x>

- Roemaker, D. L., Thompson, C. P., & Brown, S. C. (1971). Comparison of measures for the estimation of clustering in free recall. *Psychological Bulletin*, 76(1), 45–48.
<https://doi.org/10.1037/h0031355>
- Rowland, C. A. (2014). The Effect of Testing Versus Restudy on Retention : A Meta-Analytic Review of the Testing Effect. *Psychological Bulletin*, 140(6), 1432–1463.
<https://doi.org/10.1037/a0037559>
- Rudoy, J. D., Voss, J. L., Westerberg, C. E., & Paller, K. A. (2009). Strengthening individual memories by reactivating them during sleep. *Science*, 326(5956), 1079.
<https://doi.org/10.1126/science.1179013>
- Sadeh, T., Ozubko, J. D., Winocur, G., & Moscovitch, M. (2014). How we forget may depend on how we remember. *Trends in Cognitive Sciences*, 18(1), 26–36.
<https://doi.org/10.1016/j.tics.2013.10.008>
- Sadeh, T., Ozubko, J. D., Winocur, G., & Moscovitch, M. (2016). Forgetting Patterns Differentiate Between Two Forms of Memory Representation. *Psychological Science*, 27(6), 810–820.
<https://doi.org/10.1177/0956797616638307>
- Schapiro, A. C., Mcdevitt, E. A., Rogers, T. T., Mednick, S. C., & Norman, K. A. (2017). Human hippocampal replay prioritizes weakly-learned information and predicts memory performance. *Nature Communications*, 9:3920. <https://doi.org/10.1038/s41467-018-06213-1>
- Schreiner, T., Doeller, C. F., Jensen, O., Rasch, B., & Staudigl, T. (2018). Theta Phase-Coordinated Memory Reactivation Reoccurs in a Slow-Oscillatory Rhythm during NREM Sleep. *Cell Reports*, 25(2), 296–301. <https://doi.org/10.1016/j.celrep.2018.09.037>
- Schuetze, B. A., Eglington, L. G., & Kang, S. H. K. (2019). Retrieval practice benefits memory precision. *Memory*, 27(8), 1091–1098. <https://doi.org/10.1080/09658211.2019.1623260>
- Sinclair, A. H., & Barense, M. D. (2019). Prediction Error and Memory Reactivation: How Incomplete Reminders Drive Reconsolidation. *Trends in Neurosciences*, 42(10), 727–739.
<https://doi.org/10.1016/j.tins.2019.08.007>
- Sutterer, D. W., & Awh, E. (2016). Retrieval practice enhances the accessibility but not the quality of memory. *Psychonomic Bulletin and Review*, 23(3), 831–841. <https://doi.org/10.3758/s13423->

- Toppino, T. C., & Cohen, M. S. (2009). The testing effect and the retention interval questions and answers. *Experimental Psychology*, 56(4), 252–257. <https://doi.org/10.1027/1618-3169.56.4.252>
- Tse, C.-S., Balota, D. A., & Roediger III, H. L. (2010). The Benefits and Costs of Repeated Testing on the Learning of Face-Name Pairs in Healthy Older Adults. *Psychol Aging*, 25(4), 833-845. <https://doi.org/10.1037/a0019933>
- Tulving, E. (1985). Memory and consciousness. *Canadian Psychology/Psychologie Canadienne*, 26(1), 1–12. <https://doi.org/10.1037/h0080017>
- van den Broek, G. S. E., Segers, E., Takashima, A., & Verhoeven, L. (2014). Do testing effects change over time? Insights from immediate and delayed retrieval speed. *Memory*, 22(7), 803–812. <https://doi.org/10.1080/09658211.2013.831455>
- Verkoeijen, P. P. J. L., Bouwmeester, S., & Camp, G. (2012). A Short-Term Testing Effect in Cross-Language Recognition. *Psychological Science*, 23(6), 567–571. <https://doi.org/10.1177/0956797611435132>
- Verkoeijen, P. P. J. L., Tabbers, H. K., & Verhage, M. L. (2011). Comparing the effects of testing and restudying on recollection in recognition memory. *Experimental Psychology*, 58(6), 490–498. <https://doi.org/10.1027/1618-3169/a000117>
- Wing, E. A., Marsh, E. J., & Cabeza, R. (2013). Neural correlates of retrieval-based memory enhancement: An fMRI study of the testing effect. *Neuropsychologia*, 51(12), 2360–2370. <https://doi.org/10.1016/j.neuropsychologia.2013.04.004>
- Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, 46(3), 441–517. <https://doi.org/10.1006/jmla.2002.2864>
- Yonelinas, A. P., Aly, M., Wang, W. C., & Koen, J. D. (2010). Recollection and familiarity: Examining controversial assumptions and new directions. *Hippocampus*, 20(11), 1178–1194. <https://doi.org/10.1002/hipo.20864>
- Zaromb, F. M., & Roediger, H. L. (2010). The testing effect in free recall is associated with enhanced organizational processes. *Memory and Cognition*, 38(8), 995–1008. <https://doi.org/10.3758/MC.38.8.995>