The double-edged sword of memory retrieval

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Abstract | Accurately retrieving information from memory boosts later retrieval. However, retrieving memories can also open a window to errors when erroneous information is retrieved or when new information is encoded during retrieval. Similarly, the process of retrieval can influence recall of related information, either inhibiting or facilitating it depending upon the situation. In addition, retrieving or attempting to retrieve information can facilitate encoding of new information, regardless of whether the new information is correct or incorrect. In this Review, we provide selective coverage of the influences of memory retrieval in three distinct arenas: effects on the retrieved information itself, effects on retrieval of related information, and effects on information encoded just after an event is retrieved. Consideration of both positive and negative effects of retrieval in these three domains is critically important to understanding the complexity of retrieval processes and their effects. We discuss episodic context as a conceptual umbrella relevant to all these retrieval effects and note key directions for future research.

Retrieval, the act of accessing information from memory, is one of the most important aspects of human learning and remembering[1]. Information that is encoded and stored but not retrieved has little use to the cognitive system. Being able to retrieve memories allows one to use stored knowledge for many purposes — including to pursue plans and behave in a goal-directed fashion, to possess a sense of self across time, and to establish and maintain social connections with others[2]. Retrieval can take the form of recall, in which one searches memory for a specific piece of information and is able to produce it. Going to the grocery store without a shopping list and suddenly remembering to buy artichokes for dinner is an example of successful recall. Retrieval is also involved in recognition, as when a person judges that they have seen or encountered something before. Hopping on the bus and identifying a familiar face as an acquaintance from work is an example of successful recognition. Thus, recall involves production of information from memory, whereas recognition involves remembering that a presented event has occurred previously.

The learning and memory process consists of four stages, with retrieval as the final stage (FIG. 1). The life of a memory starts with encoding, a process in which information enters the cognitive system through direct experience. Information is encoded together with the context in which it was encountered, such as the time, features of the environment and the person's concurrent thoughts and moods[3,4]. Subsequently, the information, together with these contextual links, can be stabilized or consolidated and then saved (stored) in memory. The fourth stage is retrieval, in which memories are brought back into conscious awareness. Retrieval can be expressed overtly, with an external expression of the memory (saying it or writing it), but it can also happen covertly, in thoughts only. Retrieving information from memory is assumed to (partly) reactivate contextual features of the original experience, owing to the connections forged between the information and the surrounding context at the time of encoding. Similarly, being in an environment that shares features with the original encoding context can also facilitate retrieval of the information[5,6]. The encoding specificity principle states that retrieval will be better to the extent that the features (cues) encoded from the environment during retrieval overlap with the features extracted during encoding[7].
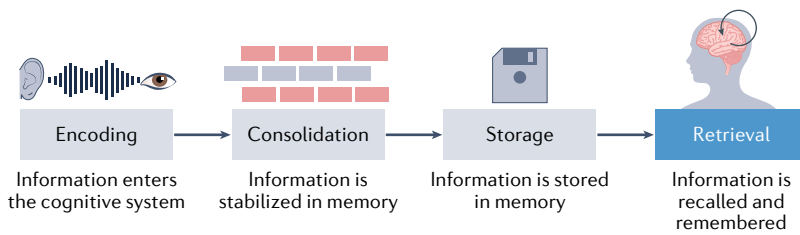
To some degree, encoding, consolidation and storage occur for every event that one experiences (with a sufficient degree of attentiveness) in daily life. Consider grabbing a quick cup of coffee somewhere in the neighbourhood. The experience is initially encoded, along with further contextual information, such as the weather or your thoughts while waiting for the coffee. As time passes, the experience is also consolidated and stored in memory, such that you could remember it a couple of days later, for example, if someone asks whether you have been to this specific café. Over a lifetime a person will encode, consolidate and store perhaps millions of events. However, the vast majority of those events, even

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Encoding	Consolidation	Storage	Retrieval
Information enters the cognitive system	Information is stabilized in memory	Information is stored in memory	Information is recalled and remembered

Fig. 1 | **Four stages of memory.** After initial encoding, memories are consolidated, stored in memory, and then retrieved. According to some accounts, consolidation processes are repeated after retrieval (reconsolidation).

if initially well stored, will never be retrieved. Retrieval is the requirement for past experience to have an impact in the present.

The act of retrieval is not a neutral process, because it influences and also partly changes what is remembered. Indeed, retrieval has complex and multifaceted effects, both positive and negative, on later remembering. Researchers often simplify the study of retrieval by focusing on one specific effect (for example, the effect of testing or retrieval practice[8]) and ignoring others.

In this Review, we consider three aspects of retrieval from memory, each with both positive and negative effects. First, we examine the consequences of retrieving information from memory on future retrieval of the same information. Depending on the circumstances, these effects can aid or distort future retrieval of the information. Second, we review the effects of retrieving information on the ability to recall related information, describing retrieval-induced forgetting and retrieval-induced facilitation. Third, we consider the dual effects of retrieval on future encoding of new information, discussing test-potentiated learning and retrieval-enhanced suggestibility. These three facets of research are critically important to understanding the double-edged sword of retrieval, or how the same process can have positive or negative consequences depending on the circumstances. Finally, we discuss a possible theoretical connection between retrieval effects in terms of context and propose promising future directions for research.

Effects on retrieved information

Imagine you go to a movie and shortly afterwards you meet a friend for coffee. She asks you to tell her about the movie, so you spend ten minutes retrieving and explaining the plot. Although it might seem simple, this initial act of retrieval has consequences for your memory of the movie, influencing how you retrieve it on subsequent occasions. These consequences of retrieval on the information being retrieved are the topic of this section.

Enhancing memory via retrieval. The act of accurately retrieving information at one point in time increases the likelihood that the information will be accurately retrieved at a later point in time[9,10]. This phenomenon is referred to as the testing effect — because tests of memory require retrieval — or the retrieval practice effect. This effect is often examined with verbal materials, such as textbook passages or vocabulary pairs, but has also

been observed for other types of material, including nonverbal ones such as visuospatial locations on a map or colour gradients[11,12].

Studies of the retrieval practice effect include a comparison condition in which participants do not engage in any retrieval practice or in which they engage in some other kind of practice with the information such as a rereading or restudying the material[8,13] (FIG. 2a). In such a control condition, participants are re-exposed to the same information that participants in the retrieval practice condition retrieve. However, usually the retrieval practice condition confers much greater benefits than the control condition. The retrieval practice effect is even more pronounced if participants in the retrieval condition are given feedback on their failed retrieval attempts. The retrieval practice effect also often occurs more strongly when the final test is delayed (often by 1–7 days) rather than conducted immediately after practice[9,14]. In fact, repeated rereading (a control condition) can lead to greater benefits than retrieval practice without feedback on a test given immediately after practice. In addition, retrieval (relative to rereading) sometimes leads to greater transfer when the same information is needed in a novel circumstance[15,16], although not always[17,18].

The retrieval practice effect is often studied in the context of education, in an attempt to understand the conditions that are most advantageous for efficient learning. Retrieval practice effects are of particular importance for applied educational contexts, in which evaluation of learners often relies on assessing how well previously studied information can be retrieved later on. Reviews and meta-analyses of retrieval practice effects consistently show the power of retrieval in enhancing long-term retention[19–22]. This evidence is backed up by studies in classrooms and similar applied settings (for reviews and meta-analyses of this applied work, see REFS.[19,21,23,24]).

Although retrieval practice effects are generally positive relative to control conditions that do not involve retrieval, different types of practice test result in different-sized effects. According to one meta-analytic review, when initial test performance was high or when corrective feedback was provided, free recall practice tests produced the greatest retrieval practice effects ($g = 0.81$), cued recall practice tests produced somewhat less of an effect ($g = 0.72$), and recognition practice tests produced a smaller (but still highly reliable) effect ($g = 0.36$) relative to restudy control conditions[20]. However, other meta-analytic reviews that focused on applied educational settings and classroom learning reported that practice quizzes in the form of multiple choice recognition tests can also produce medium to large retrieval practice effects ($g = 0.57$ (REF.[21]) and $g = 0.70$ (REF.[19]), respectively). One of these meta-analyses also found similar effect sizes irrespective of whether practice formats relied on recall or recognition ($g = 0.52$ in both cases)[21]. One study found that true–false retrieval practice tests combined with correct-answer feedback can produce a retrieval practice effect (on final short-answer as well as true–false tests) of about the same size as multiple-choice tests do ($d = 0.67$, relative to a rereading control condition)[25]. On the one hand, a retrieval practice effect might be expected from both types of test;

true–false and multiple-choice tests both involve recognition of the information learned. On the other hand, a testing effect for true–false retrieval practice relative to rereading might be surprising because participants reread the critical true items in this format just as they do in the rereading condition. Deciding on and selecting the correct answer (relative to rereading alone) seems to provide a boost to later retention.

If retrieval attempts are spaced apart in time, rather than immediately adjacent, the testing effect increases[26]. Thus, a critical factor for implementing effective retrieval practice is the spacing of practice tests[27]. For instance, one study showed a 200% benefit of spaced retrieval practice relative to back-to-back retrieval practice for Swahili–English word pairs[28]. An early study showed that expanding retrieval practice (providing a longer time between each subsequent practice test) led to greater recall later on a final test given shortly after practice, relative to retrieval practice spaced at equal intervals. However, later research, although replicating this procedure and result on an immediate test, showed that equal-interval retrieval produced greater gains than expanding retrieval on a delayed test, a result replicated several times[29,30]. These results were obtained with relatively short retention intervals, even for the delayed test. Other research indicates that an expanding retrieval schedule might be more beneficial for much longer intervals, such as ones used in real-life situations outside an experimental context (days and weeks rather than minutes)[31,32]. The optimal level of spacing probably

depends on the type and complexity of the materials and the skills of the learner.

Several theoretical accounts have been proposed to explain the retrieval practice effect, but no consensus has been reached. Retrieval-related enhancement has been attributed to transfer-appropriate processing. Retrieval practice is more similar to subsequent retrieval than re-reading (or other control condition processes) is to retrieval, which might provide direct benefits of transfer. In effect, the mental processing necessary during practice might carry over to the mental processing necessary at a later test[10,33]. However, enhancement has also been ascribed to the greater mental effort necessary during retrieval practice relative to other practice formats[26,34], or to more elaborative semantic processing of the materials during retrieval practice relative to other formats[35–38]. Retrieval practice seems to enhance mostly what is called item-specific processing (that is, processing of individual pieces of information) and provide less relational processing (processing that connects different pieces of information). That is, retrieval practice often occurs for individual pieces of information and when it does, there is no benefit to overall organization across those pieces of information, which would require relational processing. However, if retrieval practice occurs on a whole set of material, as occurs in free recall tests where participants try to recall a set of information such as a list of words that was recently presented to them, then retrieval practice does aid later organization in recall, because successful free recall induces relational processing[39,40]. Another

a   Enhancement

b   Modification
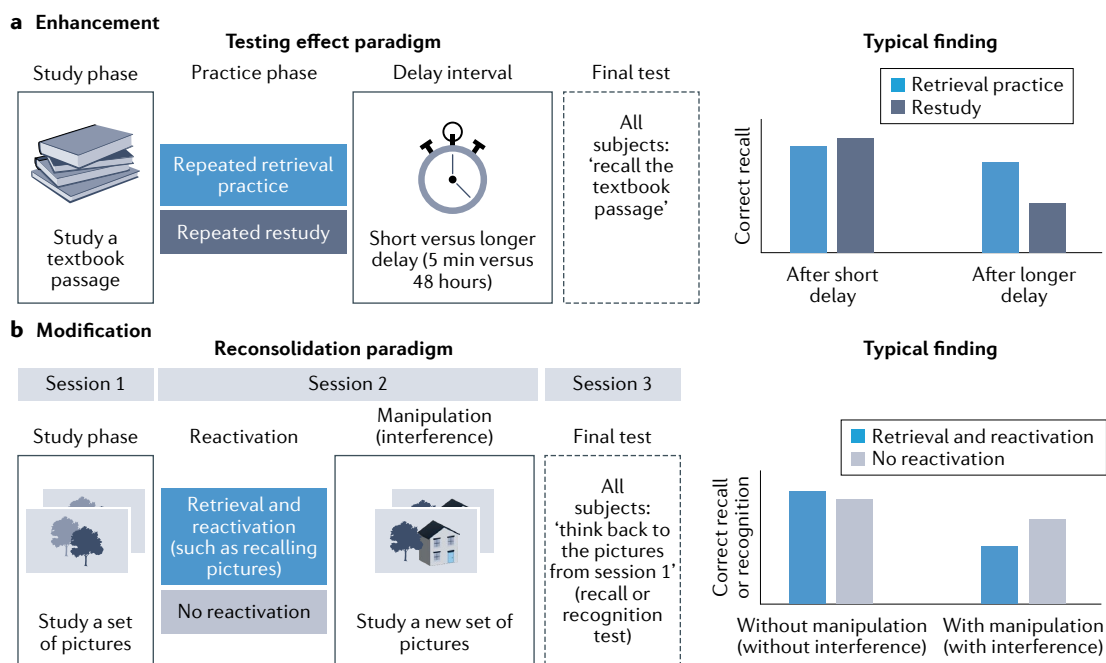
Fig. 2 | **Retrieval effects on the retrieved information. a** | A typical retrieval practice paradigm[9,10]. Participants study some information and then engage in either retrieval practice or restudy of that information. When a final memory test is conducted after a delay, participants who engaged in retrieval practice display enhanced memory relative to those who did not. **b** | A typical memory modification paradigm[54–56]. The reconsolidation paradigm consists of three sessions, separated by long delays (for example, one week apart). In session 1, participants study original materials. In session 2, some participants retrieve memory for the original materials and some participants additionally receive a further manipulation (for example, being asked to study a new set of materials). On a final test in session 3, memory for the original materials is often impaired when reactivated and paired with a further manipulation (here, interference).

proposal is that retrieval practice might reactivate the episodic context associated with the studied information and update it to include features of the practice context as well. This updated context could then serve as a more efficient retrieval cue during subsequent attempts to remember the information[41–43] (but see REF.[44]).

The act of accurate retrieval makes future accurate retrieval of the same information more likely. Practicing retrieving information from memory is as important or more important than additional efforts to store the information. In summary, describing the plot of the movie you just saw to your friend makes it more likely that you will also be able to recall it on future retrieval occasions.

Modifying memory via retrieval. If an error creeps into your description of the movie, a retrieval practice effect can also occur for the erroneous information. Thus, that error might be remembered as part of the plot in the future. The more the error is repeated in overt or covert retrieval (for example, when thinking about the movie and telling the story to yourself), the more it will become a part of your memory for the movie[45].

The misinformation paradigm was introduced to study the memory effect of new information introduced after the to-be-remembered event. For example, in one famous study[46], all participants watched a video of a car running a stop sign. Later, some participants were asked "How fast was the car going when it passed the yield sign?" while others were not. The yield sign question required retrieval but also provided misinformation — the original sign was a stop sign, not a yield sign. When participants who were asked this question were later asked whether the sign at the intersection was a yield sign or a stop sign, they were more likely to incorrectly retrieve that the original video included a yield sign than participants who did not receive this misinformation. The act of hearing about the erroneous information about the sign increased recall of misinformation on a later test, relative to a condition that did not receive misinformation[47]. In addition, the act of recalling misinformation on a first test boosts its later recall on a second test — a retrieval practice effect for misinformation. We will revisit the misinformation paradigm below in a different context.

Retroactive interference refers to the interfering effect of learning later information on recall of information already learned. For example, if you learned a poem perfectly and then learned a second poem perfectly, recall of the first poem would be impaired (relative to a control condition that did not involve new learning). The misinformation effect provides another example of retroactive interference in a more naturalistic paradigm than learning poems, although the principles are the same.

A similar effect to retroactive interference in the misinformation paradigm has also been studied using animal models (typically mice or rats). Within this research tradition, an original learning experience is consolidated and stored in memory, resulting in a long-lasting memory trace. During retrieval, the memory trace is consulted but was not thought to be changed[48]. However, 'reconsolidation' is the idea that when a memory is retrieved, the memory trace becomes labile again and is subject to modification in the period of re-stabilization[49–51]. Reconsolidation was initially examined in animals, with chemical agents applied as manipulations. In one prominent study[52,53], after being conditioned to fear a particular stimulus (with an electric shock), rats were presented with the stimulus as a reminder of the fear to bring the memory back into an active state and then injected with anisomycin, which inhibits the protein synthesis necessary for memory consolidation. After this treatment, the rats would show less or no fear response when confronted with the stimulus again. Thus, reactivating the memory made it susceptible to modification, with a protein synthesis inhibitor preventing its renewed stabilization, thereby eliminating the fear memory. The neurobiological processes underlying reconsolidation in fear conditioning involve the amygdala in interaction with the hippocampus. The idea is that the reminder of the memory and its retrieval leads to the memory trace becoming active and labile, so that interventions can disrupt the original memory (for a review, see REF.[50]).

There is evidence for similar reconsolidation processes in humans, which again reveals how retrieval can influence memory. In a typical study, participants complete a three-session paradigm (FIG. 2b). After studying materials in a first session, a fairly long retention interval (of the order of an hour or more) ensues before the second session, ensuring consolidation of the initial memory. Next, a subset of participants retrieve and therefore reactivate memory for the original material, and then a further manipulation occurs for all participants (for example, learning of new material). At a third and final session after another longer retention interval (hours or days), memory is assessed for the originally studied materials. Additional learning after the memory has been retrieved reduces performance relative to conditions without reactivation. This result is considered an expression of memory modification and updating[54–56], as are intrusions — errors that involve retrieving the new material when trying to retrieve the original material[57]. The reactivation of the original memory in the second session opens up a window for it to be modified and affected by new material.

However, the literature on reconsolidation and updating effects in humans is mixed. Few data are available on whether different types of memory reactivation are equally likely to result in modification or updating[58,59]. Some studies have used recall tests to reactivate original memories, but others have used subtle reminders of original encoding situations instead[57], which are not likely to entail retrieval of specific encoded information. Another issue is that certain manipulations found to modify memory in one study could not be repeated in similar studies[60,61]. A meta-analysis found reactivation-induced changes in episodic memory with a mean effect size of $d = 0.29$ (REF.[58]).

More studies are needed to understand better what types of memory retrieval might result in memory modification and updating, and under what conditions. Indeed, it has also been argued that some of the updating effects observed in humans might not be due to a

neurobiological process of reconsolidation, although others clearly are. Another account of reconsolidation is provided by context updating[62–64]. Similar to the context-based explanation for the retrieval practice effect, retrieval during session 2 might reactivate the episodic context present during session 1 and update the context to include features of the episodic context of session 2 as well. During session 3, when participants finally engage in remembering the original session 1 materials, the updated encoding context might serve as a retrieval cue and prompt recall of information from both sessions 1 and 2, which could explain increased intrusions from interfering materials encoded during session 2. In both biological and more psychological accounts, proponents of reconsolidation argue that every time a memory is retrieved, an opportunity occurs for new information to be encoded. Reconsolidation can either enhance memory for the original experience (as in the retrieval practice effect studies reviewed earlier) or permit misinformation to be introduced[65].

In the misinformation and reconsolidation paradigms, both the correct information and the erroneous information are presented to the participant. Another paradigm results in a similar effect without presenting any misinformation, because the participant produces the erroneous information themselves[66]. In the Deese–Roediger–McDermott (DRM) paradigm, participants are shown lists of related words (such as 'bed', 'rest', 'awake', 'tired' and 'dream') that are all related to a critical word that is missing from the list (in this case 'sleep')[67,68]. In a later test, participants tend to falsely recall and recognize the critical word ('sleep') at very high rates. Furthermore, the more recall opportunities that participants are given, the more likely they are to recall correct words and the incorrect critical word on a final test given at some later point. The upshot is that if a person erroneously recalls an event a few times, the erroneous memory seems to be stamped in and have the same mental status as information accurately recalled. The retrieval practice effect therefore occurs for both accurate and false recall.

In summary, repeated retrieval provides an opportunity for errors to creep into recollections of events. When someone retrieves events long after their occurrence, current context can re-shape the recollections.

The memory traces of past events have been referred to as 'restless'[65], becoming stronger, weaker or altogether different as they are repeatedly retrieved.

Effects on related information

Retrieval from memory often does not include everything that could be retrieved; people tend to focus on what is most important or most relevant given their current goal or situation. For instance, eyewitnesses to a crime might initially focus on reporting details of the crime itself while neglecting to report less focal aspects of the witnessed scene such as the clothes the perpetrator was wearing. Similarly, friends reminiscing about an event from their shared past might focus on the most pleasant and enjoyable aspects while avoiding embarrassing or stressful details. Early research suggested negative effects of selective retrieval, whereas more recent research suggests that selective retrieval can benefit recall of related information under certain conditions. We begin by reviewing negative effects of selective retrieval, and then move on to positive effects.

Self-limiting retrieval. A rather intuitive assumption is that memory retrieval, once successfully initiated, should progress naturally, with each remembered event increasing the chances of remembering associated events. However, early findings indicated that successful recall of one piece of information restricts subsequent recall of related information. In short, retrieval is a self-limiting process[69,70].
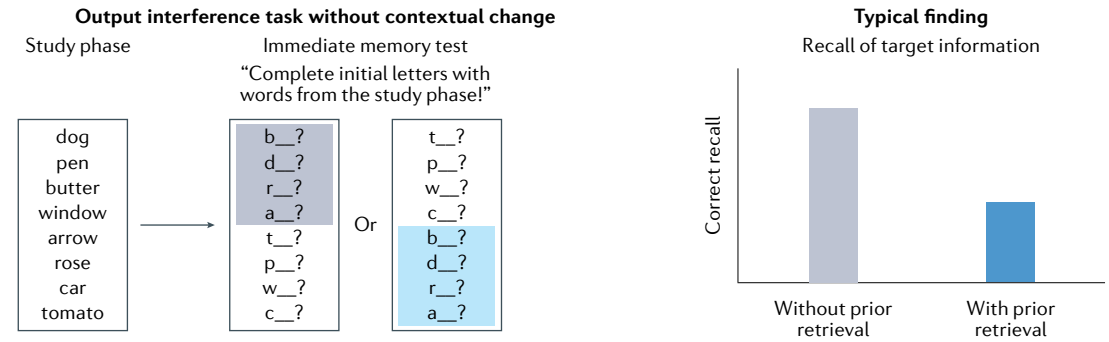
The first studies of the self-limiting nature of retrieval provided evidence for recall interference (also known as output interference)[71–73]. These terms refer to the probability of successful recall declining with preceding retrieval of different information. When recalling multiple items, items that are cued to be retrieved later in a test are less likely to be retrieved successfully than items cued to be retrieved earlier in a test. This pattern was initially reported using paired associates — that is, pairs such as single digits with words (for example, 6–rose, 4–chair, 9–termite) as study materials[71] with the test providing just the numbers in a random order. However, the same effect also holds for semantically categorized materials such as examples of furniture (such as desk, table, or bureau), of sports (such as tennis, soccer, or basketball) and of trees (such as oak, pine, or sycamore). In the test, the category names are provided in a random order for recall of items within the categories[72,73]. Output interference also occurs with lists of unrelated words[74] and facts[69,75].

Output interference has mostly been attributed to a theory called strength-based blocking[76,77]. Successful retrieval of some items early in the test strengthens these items in memory. Later in the test, when trying to recall related information, the already retrieved and strengthened information continues to be retrieved, effectively blocking access to the (unstrengthened) remaining information (BOX 1). Output interference has most frequently been examined in cued recall tests but can also arise on recognition tests[78,79] (FIG. 3a).

Another line of research also suggests that selective retrieval negatively influences retrieval of related

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Box 1 | The inhibiting effects of recall

The idea that interference in memory is due to 'response competition' is quite old[154]. In one example paradigm, one group of participants in the USA studied a list of 25 USA states while another such group read an unrelated text[69]. Each group was then given ten minutes to recall the names of all the states. If recall is purely self-propagating, then participants in the group that had studied a subset of the states would have a head start; the boost in recall for the studied states should lead to greater recall of the other 25 states. However, recall of non-list states was worse for the study group than the control group. In further experiments, this effect was replicated with UK students studying some of the counties of England before attempting recall of the entire set[69].

From these results, it was argued that multiple acts of retrieval are analogous to sampling with replacement, in which each item's likelihood of being selected is based on its strength. Successful study and retrieval of an item increases its strength in memory, so that already-retrieved items are likely to be retrieved again when participants are trying to retrieve further items. Rather than propagating and improving retrieval of related information, recall of some items can inhibit or block recall of related items.

a Retrieval limits itself

Output interference task without contextual change

Study phase

Immediate memory test
"Complete initial letters with words from the study phase!"

Typical finding
Recall of target information

Fig. 3 | **Retrieval effects on related information. a** | A typical paradigm demonstrating how retrieval limits itself. Participants study a list of unrelated words and then immediately complete a memory test. Here, they are provided with the initial letters of some words and asked to complete them using the words from the study phase. Importantly, cues are presented such that target information is recalled either right at the beginning of the memory test (grey) or at the end of the test (blue), after retrieval of the remaining nontarget information. Memory for the target information is usually worse after a nontarget retrieval, suggesting that retrieval might limit itself. **b** | A typical paradigm demonstrating how retrieval propagates itself. When contextual change is prompted after a list of unrelated words was studied (for example, by introducing a prolonged retention interval, or by triggering a substantial change in mental context), preceding retrieval of nontarget information can increase subsequent recall of target information. Figure modelled after REFS.[105–107].

information. In a phenomenon known as retrieval-induced forgetting, repeated retrieval of a subset of previously studied information can prompt forgetting of related information, even when memory is assessed a short time later[80–82]. Consistent with the retrieval practice effect literature, repeated retrieval enhances memory for the directly practised items relative to a control condition without any practice — but also impairs memory for items related to the practised materials. Retrieval-induced forgetting is often examined with semantically categorized study materials, such as types of fruit[80], but has also been demonstrated for other types of information that is grouped during study[83], for autobiographical memories[84], in eyewitness scenarios[85] and in social settings with exposure to other people's retrieval[86,87]. Regarding memory for real-world events, retrieval-induced enhancement for practised contents seems to be maximized by repeatedly practicing only very specific information, whereas retrieval-induced forgetting of related information might be maximized by practising retrieval of as much related information as possible[88].

One proposed explanation of the impairment in retrieving related items is that forgetting might be caused by inhibitory control processes that operate during practice to resolve interference arising from related information in memory. That is, in order to search for one target word, other competing words in memory must be inhibited[80,89]. Similar to output interference, retrieval-induced forgetting has also been attributed to strength-based blocking[90,91], with some authors arguing that blocking and inhibition might both play a part in producing the effect[92,93]. Another proposal is that retrieval practice might prompt a change in mental context, resulting in distinct contexts for the initial study phase and the practice phase. When some practised information is produced at test, the context related to that information becomes highly accessible. Related but unpractised information is not associated with the practice context, and the contextual mismatch results in lower recall of this information[94,95] (but see REFS.[96–98]).

Together, the findings on output interference and retrieval-induced forgetting consistently show that retrieval of some information is detrimental to and limits the retrieval of related information. However, retrieval does not always limit itself — it can have the opposite effect and propagate recall of related information under certain conditions.

Self-propagating retrieval. The notion that memory retrieval can propagate itself (known as retrieval-induced facilitation) is a natural progression of the work on retrieval-induced forgetting. Using educationally

relevant prose passages as study materials, selective retrieval practice created facilitation effects for related but untested materials, relative to a control condition without any intermittent practice[99]. These facilitation effects emerged after relatively long retention intervals of 24 hours between selective retrieval practice and a final memory test. The largest benefits of retrieval practice still occurred for directly practised information but related information also benefited with this long delay.

Follow-up studies[100,101] examined why selective retrieval practice sometimes creates forgetting and sometimes facilitation for related materials. Two potentially critical factors seem to be the degree of integration among studied information and the retention interval between selective retrieval practice and the final test. In particular, retrieval-induced facilitation for non-tested materials only emerged if study materials were presented in a coherent (rather than random) order and when the final memory test was conducted after a long retention interval of 24 hours or even 7 days (rather than after a shorter interval of 20 minutes). Importantly, if only a high integration of study materials or a longer retention interval was implemented, selective retrieval practice created no facilitation relative to a no-practice control condition. If integration of study materials was low and only a short retention interval was placed before the final test, selective retrieval practice resulted in retrieval-induced forgetting of the related materials. Thus, semantic integration as well as the delay interval between selective retrieval practice and a final test modulate whether selective retrieval limits or propagates itself.

A second line of work suggesting that memory retrieval can propagate itself refers to the 'two faces' of selective memory retrieval. This approach stresses the relevance of context retrieval for modulating the consequences of selective retrieval[102]. A basic tenet of many computational models of memory is that information is encoded and stored together with aspects of the temporal context in which it was encountered[3]. Temporal context can comprise external, environmental aspects surrounding the individual, as well as internal aspects, such as moods, thoughts and other mental activity. Context retrieval refers to the idea that recall of a memory partly reinstates or brings back the context that was present when the memory was formed, and that such retrieval can aid and prompt recall of other related memories that were encoded in temporal proximity[103,104]. Classic work on retrieval as a self-limiting process mostly examined retrieval under conditions that did not make context retrieval necessary, because relatively short retention intervals were used and hardly any contextual change occurred between encoding and retrieval[102].

A series of studies used unrelated lists of words as study materials and specifically varied contextual change across encoding and retrieval (for example, by placing longer retention intervals between initial encoding and selective retrieval practice, or by triggering post-encoding contextual change through imagination and directed forgetting tasks[74,105–107] (FIG. 3b). The results consistently showed two opposing effects. On the one hand, selective retrieval of some list items prompted forgetting of the remaining items when there was hardly any contextual change between study and test (for example, after short delays). On the other hand, selective retrieval propagated recall of the remaining items when higher levels of contextual change were evoked (for example, after long delays or after instructions to forget or engage in imagination tasks). These patterns suggest that selective retrieval is associated with inhibition and/or blocking as well as facilitation from context retrieval or reinstatement. Which of these processes dominates at a given point in time might depend on the degree of contextual overlap between the test and the encoding context. When hardly any contextual change has occurred, overlap is high and inhibition and/or blocking might operate to resolve interference among pieces of information, limiting retrieval of further information. With substantial contextual change and low overlap, the potential for interference might be low and context retrieval helps to reinstate the original encoding context, thereby propagating retrieval of further information[102,108].

In sum, findings on retrieval-induced facilitation and the 'two faces' of selective memory retrieval show that partial retrieval does not always have detrimental consequences for retrieval of related information but can also enhance it. The latter findings might not only be a relief to anyone who engages in selective retrieval in daily life (for example, eyewitnesses, or friends reminiscing about the past), but might also reconcile the scientific literature with intuitive expectations regarding selective retrieval.

Effects on subsequent encoding

We have reviewed the effects of retrieval on memories that were already encoded beforehand. However, memory retrieval can also impact subsequent encoding and learning. As a student, you might have studied hard for an organic chemistry exam and then, after the test, tried to banish the topic from your mind to study for an upcoming history exam. Perhaps surprisingly, the act of taking the chemistry test can improve the efficacy of subsequent history studying, for both accurate and inaccurate facts. Once again, these indirect effects of memory retrieval can be grouped into beneficial and detrimental effects: test-potentiated learning and test-enhanced suggestibility.

Test-potentiated learning. Memory tests can not only increase memory for the retrieved information, but also enhance subsequent new learning, a finding referred to as test-potentiated learning or the forward effect of testing[109–111]. After unsuccessful retrieval attempts, restudy or relearning opportunities for the original information make it easier to relearn. More attempts to retrieve the original information potentiate what can be gained from restudying it, relative to conditions with fewer (or zero) retrieval attempts[112–114]. Indeed, benefits of initial retrieval attempts can even emerge when successful retrieval is made impossible by use of vague cues[115,116].

Test-potentiated learning also occurs for completely new learning that is unrelated to the retrieved information. For instance, in a learning task with unrelated lists of words, if retrieval practice is interpolated after each

studied list, memory is increased for a subsequently studied list, relative to control conditions with interpolated restudy or other non-retrieval activities (FIG. 4a). Test-potentiated new learning has been demonstrated with unrelated lists of words and word–word paired associates[117–119], prose texts[120] and lecture videos[121,122].

Test-potentiated learning has clear relevance for applied educational contexts, in which learners often face sustained periods of encoding new information. For instance, students encounter many new facts in multiple different subjects across the school day. Interpolated tests (for instance, after each class) might help to better segregate different information from each other and therefore provide benefits for learning of new materials in the subsequent class. However, this particular claim has not been tested in a classroom situation. Within a specific class, interpolated retrieval practice can be beneficial for maintaining attention and encoding capacities for materials across different class sections[121]. An issue that has not yet been examined is whether test-potentiated learning wears off with repeated and maybe even routine use in classrooms and other real-life learning contexts.
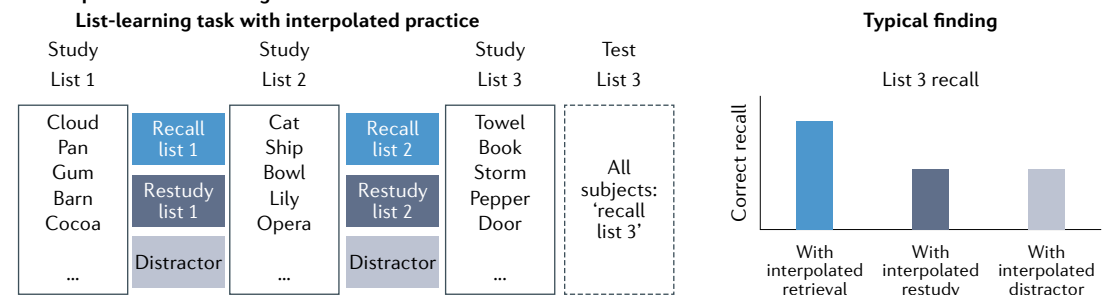
There are multiple accounts of the cognitive mechanisms behind test-potentiated learning in the literature[109–111]. One proposal is that interpolated retrieval increases contextual change and thereby results in better contextual segregation of all studied sets of materials. As a consequence, proactive interference, or interference from previously studied information, might be reduced, which facilitates memory for subsequently studied new information, such as the history text in our example[118,119,123]. Another proposal is that interpolated retrieval might directly influence new encoding. For instance, interpolated retrieval might trigger a reset of encoding processes, which enhance and sustain attentional capacities across a series of study cycles and therefore maintain encoding efficiency[119,121]. Alternatively, the experience of previous memory tests might encourage learners to switch to more effective or elaborative study strategies when asked to engage in additional learning later on[124–126]. These and similar changes in encoding might then directly mediate test-potentiated learning of new information.
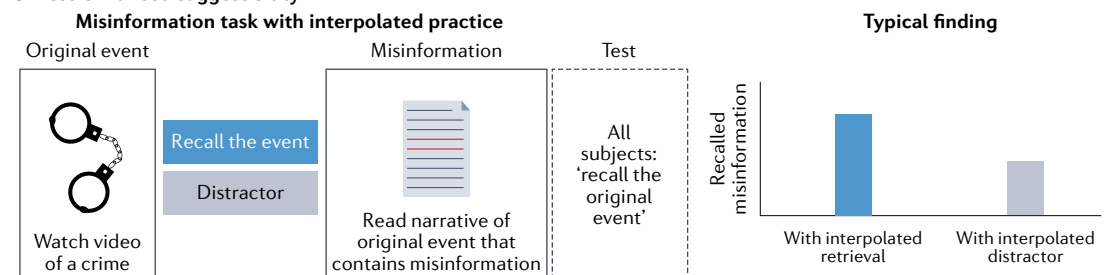
Test-enhanced suggestibility. In addition to the positive effects of retrieval improving learning for subsequently presented accurate information, memory retrieval also enhances learning of subsequently presented misinformation. This misinformation can potentially result in distortion of the originally encoded memories, known as test-enhanced suggestibility.

Research on the misinformation effect[46,127], discussed above, has consistently shown that memory for an originally witnessed event can be altered when new information is encountered. Importantly, the misinformation effect not only occurs for plausible details added to the original event, but also for information that directly contradicts what was originally encoded[46,128,129]. That is, if the criminal used a knife in a robbery (as originally shown to participants), the misinformation might say he used a screwdriver. However, if the contradiction provided by new information is sufficiently blatant, the misinformation actually causes better recall of the original information than when no misinformation is present[130]. In addition, for information that is correct in

a   Test-potentiated learning

List-learning task with interpolated practice

Typical finding

b   Test-enhanced suggestibility

Misinformation task with interpolated practice

Typical finding

Fig. 4 | **Retrieval effects on subsequent encoding. a** | Typical paradigm demonstrating test-potentiated learning[118,119]. Participants study several unrelated lists, with interpolated practice in the form of recall, restudy or a distractor task after each list. Memory for the final target list is usually enhanced after interpolated recall, relative to after restudy or after distractor tasks between lists. **b** | Test-enhanced suggestibility in a typical misinformation paradigm[132,134]. Participants encode an original event, for instance by watching a video of a crime, and then either recall the event or engage in an unrelated distractor task before being exposed to misinformation about the original event. On a final test, participants who completed the interpolated recall test recall higher amounts of misinformation.

Table 1 | **Three opposing effects of memory retrieval**

Information affected	Positive effects	Negative effects
Retrieved information	With accurate retrieval (recall or recognition), later retention is improved	The act of retrieval opens a window for possible changes in memory from both external and internal influences
Related information	In some circumstances, the act of retrieval can lead to retrieval of related information	The act of retrieval can inhibit recall of related information under other conditions
To-be-encoded information	The act of retrieval can facilitate encoding of additional information	The act of retrieval can facilitate encoding of misinformation

the narrative, recall or recognition is improved on the final test, another case of test-potentiated learning.

Parallel to findings on test-potentiated learning, several studies indicate that interpolated retrieval practice after initial encoding of an event can also enhance memory for post-event misinformation[131–135]. Participants complete a typical misinformation paradigm, but after encoding the original event and before encountering misinformation, some take a test on the witnessed event whereas others engage in unrelated distractor activities. Critically, interpolated retrieval from the test enhances the encoding of misinformation, leading to higher rates of adopted misinformation or a greater misinformation effect (FIG. 4b). Interpolated retrieval practice therefore seems to increase suggestibility. Returning to the applied eyewitness scenario, initial police interviews or retellings of the event might make eyewitnesses to a crime more vulnerable to encoding later misinformation about the event.

Test-enhanced suggestibility can be conceptualized as test-potentiated learning of misinformation. Thus, some of the potential mediators of test-potentiated learning might also act as potential mediators of test-enhanced suggestibility[136]. For instance, the proposals that retrieval can maintain attentional encoding efficiency or trigger switches to more optimal encoding strategies could also account for why interpolated testing might lead to retention of post-event misinformation. Some additional accounts that are more specifically aimed at explaining test-enhanced suggestibility have also been proposed. For instance, reconsolidation processes have been suggested to play a role: retrieval of the original memories could leave them in a labile state and susceptible to retroactive interference from misleading information in the form of misinformation[133]. Further ideas are based on the view that retrieval could change how post-event misinformation is taken in. Retrieval might increase the perceived credibility of post-event misinformation[137] or might directly change how post-event information is processed and encoded[134,135,138]. These and similar theoretical accounts are still being debated.

Test-enhanced suggestibility is of clear relevance to eyewitness scenarios. Because inaccurate eyewitness testimony can have grave consequences, it is vital to understand under what conditions interpolated tests (for example, in the form of police interviews) increase susceptibility to post-event misinformation. Some studies

in the literature provide a counterpoint to the work on test-enhanced suggestibility. Several studies suggest that retrieval does not necessarily render memories more susceptible to retroactive interference but can actually protect them from the detrimental effects of subsequent encoding. That is, retrieval practice of the original information seems to reconsolidate it and make it less likely for misleading information to be acquired[139–141]. Similarly, a number of other studies reported patterns quite opposite to test-enhanced suggestibility, with retrieval practice protecting memories from misinformation and social contagion effects[142–145]. More work is necessary to clarify when retrieval distorts and when it protects memories for originally encoded information.

The work on test-enhanced suggestibility shows that test-potentiated learning can result in clear-cut benefits for memory but also in memory distortions. As with our previous two contrast pairs, effects of retrieval on subsequent encoding can become detrimental when new encoding consists of misinformation. To follow the earlier example, if you study some inaccurate history material after taking your organic chemistry exam, you might end up remembering more of the history material — including the inaccuracies.

The role of context in retrieval

The phenomena reviewed here demonstrate how the same manipulation can have positive or negative consequences depending on the circumstances (TABLE 1). The opposing effects might seem paradoxical and they are not yet fully understood. However, these effects can all be linked to episodic context, lending a potential theoretical framework for understanding retrieval-related enhancement and hindrance.

Almost all of the effects considered in this Review share theoretical accounts involving episodic context. Context fluctuates naturally with the passage of time, owing to changes in environment, mood and thoughts[146,147], and it is often an effective retrieval cue for later recall of encoded information[5,6]. A central assumption is that context from one situation to another generally differs more as time passes. Theoretical proposals regarding context often build upon computational models that explore search processes in memory and stress the role of context[3,103] (for an overview, see REF.[148]). The concept of search in these models is of attention directed inward, examining a network of connected memory nodes. Memory models include the assumptions that retrieving a memory reinstates the context present during encoding and updates it to include features of the retrieval situation[103,149,150]. Moreover, some models assume that engaging in memory retrieval can increase contextual change above and beyond the gradual fluctuation of context with time[149,151].

Expanding the assumptions from these memory models leads to potential explanations of how context creates both negative and positive effects of retrieval. The episodic context account of the retrieval practice effect[41,42] is based on some of these assumptions. When memories are recalled during retrieval practice, the original episodic context is assumed to be reinstated and updated with the new context present during

retrieval. On a final test, when retrieval is attempted a second time, both the original encoding context and the updated practice context aid the search process. The act of retrieval on a first test permits greater encoding of new context information than does passive restudying, and when the event is retrieved again, the two sets of context guide memory search more effectively than the single set established during initial learning, leading to the retrieval practice effect.

Because retrieval opens a window for additional context to be stored, the episodic context account can also be applied to explain at least some reconsolidation effects. That is, when the original encoding context is reactivated and updated during retrieval, newly encoded information might be linked to the updated context as well and be retrieved later when participants try to think back to the originally encoded information to reinstate the updated context. A different way to achieve the same result is to assume that reactivation of context (from recalling encoded information) prior to learning new information links the new learning to the original context. When the old context is reactivated during a later test and people are asked to recall only the original information, the reinstated context cues both the old and new information. This account can explain how intrusions from a second learning episode can be recalled when trying to recall a first episode[62,152].

Another theoretical proposal based on episodic context explains why selective retrieval sometimes decreases and sometimes increases retrieval of related information[102,105,107]. On a test given soon after learning, the original episodic encoding context is probably easily accessible, leading to high potential for interference between two recently encoded pieces of information linked to that encoding. Under such conditions, selective retrieval of some information might cause blocking and/or inhibition of the remaining information to facilitate retrieval of the target information, under the assumption that interference between the two types of information must be resolved by suppressing one of them. When a test is given after a longer delay, access to the original encoding context is initially impaired and therefore interference potential between information is low. Under these conditions, selective retrieval of some information might help to reinstate the original encoding context, which can act as a cue for further retrieval and prompt recall of related information that was encoded in temporal proximity.

Finally, a context-based explanation has also been offered for test-potentiated learning. Interpolated retrieval practice after the study of some information and before the study of other information has been suggested to increase contextual change, enabling a better differentiation of the encoded information[118,119,123]. This increase in contextual segregation can reduce proactive interference from previously studied information and thereby facilitate memory for subsequently studied information. Increased contextual change owing to memory retrieval has also been implemented in some memory models[149,151].

Although contextual change could explain test-potentiated learning, it is not as easily compatible with test-enhanced suggestibility and an increased acceptance of misinformation after interpolated practice. However, test-enhanced suggestibility has also been conceptualized as an instance of reconsolidation[133], with retrieval rendering initially encoded memories susceptible to retroactive interference in the form of misinformation. A context-based explanation like the one described above for reconsolidation could therefore potentially explain test-enhanced suggestibility. However, such an explanation would mean that the effect is attributed to a different context-based mechanism than test-potentiated learning. Thus, this explanation would differ in character from the context explanations for the other two findings where the same mechanisms are employed.

Thus, all three of the opposite effects of retrieval can be understood using an account emphasizing the role of context. Although we have not proposed a full theory of these opposing effects, they can all be understood as manifestations of context-based influences on remembering. Memory models including context might be of value in solving how exactly the many effects of memory retrieval can be understood as a whole.

Importantly, alternative theoretical accounts not primarily based on context exist for all effects considered here. For instance, retrieval practice effects have been proposed to arise owing to semantic elaboration[35], retrieval-induced forgetting has been attributed to inhibition[80,81], retrieval-induced facilitation has been linked to semantic integration of materials[100], and test-potentiated learning and suggestibility have been suggested to arise because prior retrieval directly influences subsequent information processing and encoding[119,138]. Ultimately, many of the cognitive mechanisms and factors central to these and other accounts might also be needed for a complete picture of the interplay of memory retrieval effects.

Summary and future directions

The act of remembering changes memory in important ways. First, there are positive and negative effects of retrieval on the retrieved memories. If memories are retrieved accurately, their repeated retrieval will boost later retention, often substantially. However, if errors are retrieved repeatedly, or if misinformation is inserted and retrieved, then repeated retrieval will cement those errors. Second, there are positive and negative effects of retrieval of some information on recall of related information. If the to-be-retrieved material is semantically integrated or highly inter-associated, then retrieval of one piece of information will usually provoke retrieval of related information, especially after a delay. However, if information is not inter-associated and retrieval of some information occurs shortly after learning, then recall of related information is inhibited. Yet once sufficient contextual change has occurred (for example, after prolonged delay), retrieval can also help to reinstate the original encoding context, facilitating recall of related information. Finally, retrieving information seems to permit better encoding of new information. If the new information is correct, recall of the event is enhanced. If misinformation is presented after retrieval of the original information, then erroneous recollection of the original events will result. Episodic context, as incorporated in

many computational models of memory, can provide a unifying mechanism to explain these various effects, though work remains to flesh out this account. These three contrasting pairs of effects showcase how different and partly antagonistic the effects of memory retrieval can be. Of course, other effects exist within the broad topic of retrieval that we have not discussed here[153].

Our portrayal of memory retrieval as a double-edged sword and characterization of the effects as 'positive' and 'negative' might ultimately be too simplistic. The human cognitive system needs to be flexible to adapt to ever-changing environments. It is easy to recognize effects that boost and enhance memory performance as positive, whereas it might be harder to appreciate the upside of effects that restrict and change memory. For instance, the self-limiting quality of memory retrieval could be an asset in situations with a high load of information — it can help to resolve interference and facilitate recall of target information. Similarly, the fact that memory retrieval can destabilize memories and introduce modification might be helpful in situations in which the initially encoded information was incorrect or insufficient. As such, seemingly negative effects might confer certain advantages and ultimately be adaptive.

There are several places where more research is needed into the effects of retrieval. For example, the study of human memory using reconsolidation paradigms is in its infancy, and these paradigms need to be combined with standard cognitive psychology paradigms on retroactive interference and misinformation effects. In addition, the effect of schedules of spaced retrieval on long-term retention (over days and weeks) needs more study. For instance, it is unclear how to promote learning that will persist across years, such as when an employee wants to learn a fact or a skill that needs to last their entire work career. The answers to such questions might differ for different learners, so understanding individual differences among people becomes important. In addition, test-potentiated learning in applied settings has also received little attention to date and could be particularly important in education.

Besides these suggestions regarding specific effects, future research should integrate the various paradigms showing positive and negative effects. In the past, the tendency has been to study each of the six effects in isolation. Although more than one effect is considered in some cases — such as in retrieval-induced forgetting, where every experiment also includes data relevant to the retrieval practice effect — studying the effects in concert will bring new insight. For example, if varying one facet of retrieval causes greater retrieval-induced forgetting, perhaps it also creates greater test-potentiated learning when new information is presented after retrieval. Such questions, resulting from a combination of paradigms, should facilitate future understanding of how these effects interact.

Moreover, the many empirical findings on different effects of memory retrieval could also be used to further test the idea of episodic context as a unifying concept in memory models, and these developments could again feed back into the empirical study of memory retrieval. As context models are refined as a result of new empirical findings, they might make novel predictions that will lead to further empirical tests. Over time, we are confident that the double-edged sword of retrieval will be better understood.

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