The science of effective learning with spacing and retrieval practice

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Abstract | Research on the psychology of learning has highlighted straightforward ways of enhancing learning. However, effective learning strategies are underused by learners. In this Review, we discuss key research findings on two specific learning strategies: spacing and retrieval practice. We focus on how these strategies enhance learning in various domains across the lifespan, with an emphasis on research in applied educational settings. We also discuss key findings from research on metacognition — learners' awareness and regulation of their own learning. The underuse of effective learning strategies by learners could stem from false beliefs about learning, lack of awareness of effective learning strategies or the counter-intuitive nature of these strategies. Findings in learner metacognition highlight the need to improve learners' subjective mental models of how to learn effectively. Overall, the research discussed in this Review has important implications for the increasingly common situations in which learners must effectively monitor and regulate their own learning.

Effective learning skills are critical for navigating an increasingly complex world. Rapid advances in technology make it possible to access large amounts of information quickly. Although this transition has brought advantages in the form of faster and easier communication, it also adds new challenges for people seeking to learn amidst a myriad of options for access to and use of information.

Educational opportunities are also becoming increasingly autonomous, involving greater flexibility and more student-led decisions. A 2019 survey reported that the majority of US undergraduate and graduate students have taken at least one online course[1], and the popularity of massive open online courses is ever increasing[2,3]. Compared with traditional lessons in structured classroom environments, these online approaches involve more freedom for learners to decide how and when to engage in learning, as well as greater responsibility for learners to keep themselves on track, monitor their progress and remediate their learning when necessary.

This new educational landscape raises important questions about the best ways to learn information and how to know when one has learned something effectively. More than 100 years of scientific research on the psychology of learning have been devoted to these questions. This research has revealed some straightforward techniques that enhance learning. In particular, spacing of learning opportunities across time and incorporating active retrieval of the material are both effective in boosting learning across various domains. However, these techniques are underused by learners, in part because of false beliefs about learning and the counter-intuitive nature of the techniques.

In this Review, we discuss key research findings from the psychology of learning. We begin with an overview of how learning is typically measured. We then discuss spacing and retrieval practice, two strategies that produce effective learning. We focus on these strategies because of the long-standing research showcasing their general effectiveness and straightforward applicability in numerous learning domains[4–9]. Next, we discuss key findings in the research on metacognition — how learners monitor and make decisions about their own learning — focusing on ways in which metacognition can break down and how to improve it. Finally, we propose numerous directions for future research concerning the adoption of effective learning strategies, improving awareness of these strategies, and the knowledge and skills relevant to increasingly autonomous approaches to learning.

Measuring learning

Successful learning requires building factual knowledge as well as an understanding of how that knowledge can be integrated, utilized and applied in new situations. Memory for basic facts and concepts is needed to build a deeper understanding of how those facts and concepts fit into a broader network of knowledge, in turn allowing advanced reasoning and application[10]. Although memory for facts and concepts can be developed in the early stages of learning, a more comprehensive perspective that permits deeper understanding can be slower to

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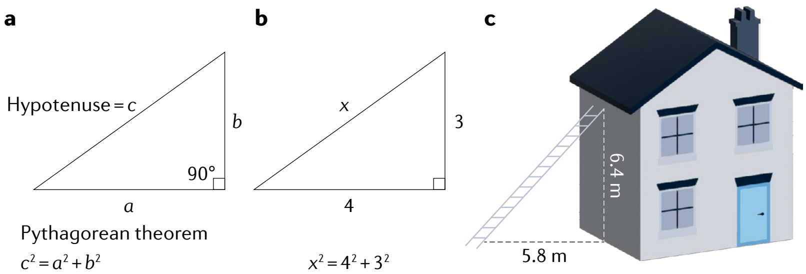

Fig. 1 | **Knowledge retention and transfer.** Pythagorean theorem describes the relationship between the lengths of three sides of a right-angled triangle. **a**–**c** | A knowledge retention test would require students to remember some piece of information that they have learned about the theorem, such as the formula for finding the length of the hypotenuse (part **a**). A knowledge transfer test would require students to answer a novel question that demonstrates understanding or application of the learned information. This might involve calculating the hypotenuse using values given for the other two sides of a new triangle (part **b**) or applying the theorem to a new situation involving a real-world example (part **c**).

develop[10]. An important objective of research on learning is to measure these different levels of knowledge. Doing so builds an understanding of the stages and time progression of learning, as well as the ways in which different learning activities might improve particular levels and types of knowledge.

In measuring learning, a distinction is commonly made between knowledge retention and knowledge transfer[11]. An example of retention and transfer can be illustrated using the Pythagorean theorem (FIG. 1). Knowledge retention is the ability to retain something in memory. One can retain the theorem, which states that in a right-angled triangle, the length of the hypotenuse squared is equal to the combined squares of the lengths of the other two sides (FIG. 1a). Knowledge transfer refers to the ability to demonstrate a broader understanding of a concept. For instance, transfer enables one to use the theorem to calculate the hypotenuse length of a right-angled triangle with side lengths that have not been previously encountered (FIG. 1b). Transfer is also required when knowledge is applied in a new context that differs from the way in which it was originally learned. Thus, transfer is also used to apply the theorem to calculate how long a ladder must be in order to reach the second storey of a building from 5.8 m away (FIG. 1c).

Transfer requires memory retention. Learners would not be able to find the hypotenuse of a new right-angled triangle without first remembering the theorem. However, learners could successfully remember the theorem but fail to recognize its relevance in a new situation. Successful transfer depends on sufficient memory for information as well as the ability to understand the relevance of that information in a new situation. Thus, transfer demonstrates a more advanced level of learning than retention. Transfer can fail owing to deficiencies in memory retention, the ability to connect remembered information to a current situation, or both[12].

Both retention and transfer are important to learning. In academic contexts, a great deal of factual information must be retained, such as theorems, principles, terms and definitions, scientific names and foreign language vocabulary. However, an important goal of learning is to utilize and apply knowledge, so transfer might be considered the ultimate goal. Transfer can occur in numerous ways, ranging from fairly simple to more complex[12]. Simple transfer is sometimes called 'near' transfer (for example, applying a mathematical formula to a new problem) (FIG. 1b) and complex transfer is called 'far' transfer (for example, applying a solution or principle from one knowledge base to another) (FIG. 1c).

A long-standing focus of research on the psychology of learning has been to uncover and understand strategies that build effective retention and transfer. The strategies of spacing and retrieval practice have been widely studied in both academic and real-world contexts, across a multitude of learning domains, involving learners from all stages of life. Below we highlight some of the key research findings in these areas, focusing primarily on studies conducted in real-world educational environments.

Strategies for effective learning

Much like a fitness routine designed to achieve a particular goal, such as weight loss or miles walked in a year, a successful learning routine requires knowing what to do and when to do it. We review key research findings on two of the most effective strategies for learning according to psychological research. Spacing is a way to structure or schedule learning activities over time (when to engage in learning), whereas retrieval practice is a learning activity that can be incorporated within a broader structured plan (how to learn effectively).

Spacing out learning across time. To build durable knowledge, learners have to repeatedly study and use the information that they are trying to learn. Whether trying to learn definitions for scientific terms, grammar rules or how to use a computer program, learners have to revisit the material multiple times in order to develop proficiency. This need is visible even in the early years of formal education, when young children are given repeated practice in reading and mathematics to develop these fundamental skills. However, few people consider the timing of this repeated practice — one might logically assume that the timing does not matter so long as learners get a sufficient quantity of practice.

As it turns out, the timing of practice greatly influences learning success, even for the same overall quantity of practice. Repeated practice opportunities that are spaced apart in time are more effective than the same number of practice opportunities that occur closer together in time. This finding — known as the spacing effect or the distributed practice effect — was first documented more than 100 years ago[13] and has been demonstrated in several hundred studies[5], making it one of the most reliable and robust findings in the psychology of learning. According to a 2006 meta-analysis, the benefits of spacing on retention of information over at least 1 day can be sizeable, sometimes with an effect size of Cohen's d greater than 1.0 (REF.[9]). Across the lifespan, spacing effectively enhances learning in numerous domains (TABLE 1). These range from 3-year-old children learning about basic concepts and categories[14] up to 60-year-old adults learning new knowledge and skills[15].

Table 1 | **Selected studies showing statistically significant effects of spacing across the lifespan**

Learner level	Learning materials	Implementation of spacing	Ref.
Preschool or younger (<5 years old)	Pictures	Pictures presented twice, separated by two, four or eight intervening pictures	160
	Toy names	Three presentations per toy spaced apart by 30 s	14
	Words	Four exposures spaced apart by 3 days	161
Elementary school (5–10 years old)	Credibility judgements	Three lessons spaced 1 week apart	18
	Foreign language translations	Two learning sessions separated by 1 week	162
	Grammatical rules	Ten practice trials spaced across 5 or 10 days	163
	Mathematical skills	Four daily sessions spaced 2–4 h apart, repeated over 18 days	164
	Pictures	Pictures presented twice, separated by two, four or eight intervening pictures	160
	Scientific principles	Four lessons spaced across 4 consecutive days	17
	Vocabulary words	Two lessons spaced 1 week apart	28
Middle school (11–13 years old)	Biology lessons	Four lessons spaced 1 week apart	42
	Credibility judgements	Three lessons spaced 1 week apart	18
	Foreign language translations	Two sessions spaced apart by 1 day	165
	Mathematics, algebra and geometry	Problems per topic spaced across eight assignments over 15 weeks	19
	Mathematics, permutations and diagrams	Three practice sessions spaced 1 week apart	16
High school (14–18 years old)	Foreign language translations	Three practice periods spaced across 3 consecutive days	166
	Mathematics, geometry	Problems per topic spaced across seven assignments over 6 weeks	20
	Physics problems	Each practice problem spaced apart by 1 day	167
	Writing in shorthand	Multiple exercises spaced apart by up to five successive lessons	168
Undergraduate	Anatomy course	Three learning sessions spaced across 1 week	169
	Artists' painting styles	Six examples per artist, presented with intervening examples	170
	Educational texts	Two readings separated by 1 week	171
	Engineering problems	Three homework sets spaced apart across 3 weeks	172
	Face–name pairs	Four presentations per pair, spaced apart by one, three or five intervening items	173
	Foreign language verb conjugation	Two sessions spaced apart by 1 week	174
	Grammatical rules	Three sessions spaced apart by 1 or 4 weeks	175
	Mathematics, pre-calculus	Three quizzes spaced apart by 1–2 weeks	26
	Mathematics, permutations	Two practice sessions spaced apart by 1 week	176
	Meteorology lessons	Two sessions spaced apart by 8 days	27
	Natural categories	Six examples per category, presented with intervening examples	177
	Physics problems	Three problems per topic spaced apart by 2 days or more	21
	Piano melodies	Three practice sessions separated by 6 or 24 h	178
	Pictures	Pictures presented twice, separated by two, four or eight intervening pictures	160
	Statistics	Three practice sessions, spaced apart by 2 or 5 days	179
	Visuospatial memory task	Four practice trials spaced apart by 15 min each	15
	Word pairs	Four practice sessions spaced across 4 consecutive days	180
	Word-processing skills	Two practice sessions spaced apart by 10 min	181
Postgraduate	Cardiopulmonary resuscitation skills	Multiple practice sessions, each spaced apart by up to 1 month	182
	Nutrition knowledge	Four learning sessions, each spaced apart by 1 week	22
	Pharmaceutical names	Two sessions of retrieval practice, separated by 2, 3, 4, 7 or 8 weeks	183
	Surgical procedures	Four training sessions, each spaced apart by 1 week	23
	Urology course	Eleven to thirteen learning exercises, each spaced 1 week post lesson	184
Older adults (>50 years old)	Artists' painting styles	Six examples per artist, presented with intervening examples	185
	Motor skill task	Nine practice trials spaced apart by 43 s each	186
	Visuospatial memory task	Four practice trials spaced apart by 15 min each	15
	Word pairs	Word pairs presented twice, separated by 1, 4, 8 or 20 intervening pairs	187

In the design of a typical study on the spacing effect, two groups of learners have at least two opportunities to study information (FIG. 2a). These opportunities can occur either close together in time (massed learning) (FIG. 2a, top row) or farther apart in time (spaced learning) (FIG. 2a, bottom row). At a later point, learning is assessed for both groups. Even though the overall quantity of practice is the same between the two groups, learners who engaged in repeated practice that was spaced out typically show better performance on the later test. As discussed in more detail later in this section, these benefits occur for both retention and transfer of knowledge.

Spacing effects have been explored in both laboratory-based and school-based studies. Studies conducted in schools confirm that spacing can be a powerful learning strategy. In one study, spacing significantly boosted mathematics knowledge in middle school students (11–12 years old)[16]. Students worked through 12 practice problems on 2 topics by completing 4 practice problems per day for each of 3 days spaced apart by a week (spaced group) or the same 12 practice problems on the same day (massed group). Four weeks after finishing the practice problems, both groups were given a test containing new problems on the same topics; the spaced group significantly outperformed the massed group, scoring about twice as high (effect size of Cohen's $d = 0.61$).

Spacing benefits learning across domains and levels of education. In one study, elementary school children (5–7 years old) learned scientific principles associated with food chains (for example, the tendency for larger animals to eat smaller animals) through four lessons, with different spacing across three groups of students. Lessons occurred once per day across 4 days (spaced group), twice per day across 2 days (clumped group) or with all four lessons on the same day (massed group)[17]. On a test given 1 week after the lessons, children in the spaced group significantly outperformed children in the clumped and massed groups (with effect sizes ranging from Cohen's $d = 0.38$ to $d = 1.41$). Another study showed that children at the elementary school and middle school levels (9–12 years old) learned how to evaluate the credibility of information on websites more effectively if they received three lessons that were scheduled 1 week apart rather than 1 day apart[18]. At the middle school and high school levels (students who are typically about 11–17 years old), the advantages of spacing have been observed when including practice mathematics problems from previous lessons within current lessons covering different topics[19,20].

Spacing also benefits learning at the university and postgraduate levels. In one study, undergraduate physics students completed three weekly homework assignments in which questions on a given topic appeared either all in the same assignment or spread out across the three assignments and completed on different days[21] (FIG. 2b). On a later surprise test containing novel problems about the same concepts, students scored significantly higher for the topics that were spread across the different homework assignments than within the same assignment (effect sizes of Cohen's $d = 0.40$ and $d = 0.91$ for the first and second half of the course, respectively). Spacing enhanced students' memory for the formulas that were relevant to the problems, as well as students' use of the correct strategies to solve the problems. At the postgraduate level, spacing benefits medical students learning nutrition information[22] and surgical tasks[23,24]. In one study, medical students completed three blocks of hands-on surgery training all on the same day or once per week across 3 weeks[25]. On tests given both 2 weeks and 1 year after the training, the group that completed the blocks once per week performed better and faster than the massed group.

The benefits of spacing are long-lasting. One study showed significant benefits of spacing on pre-calculus

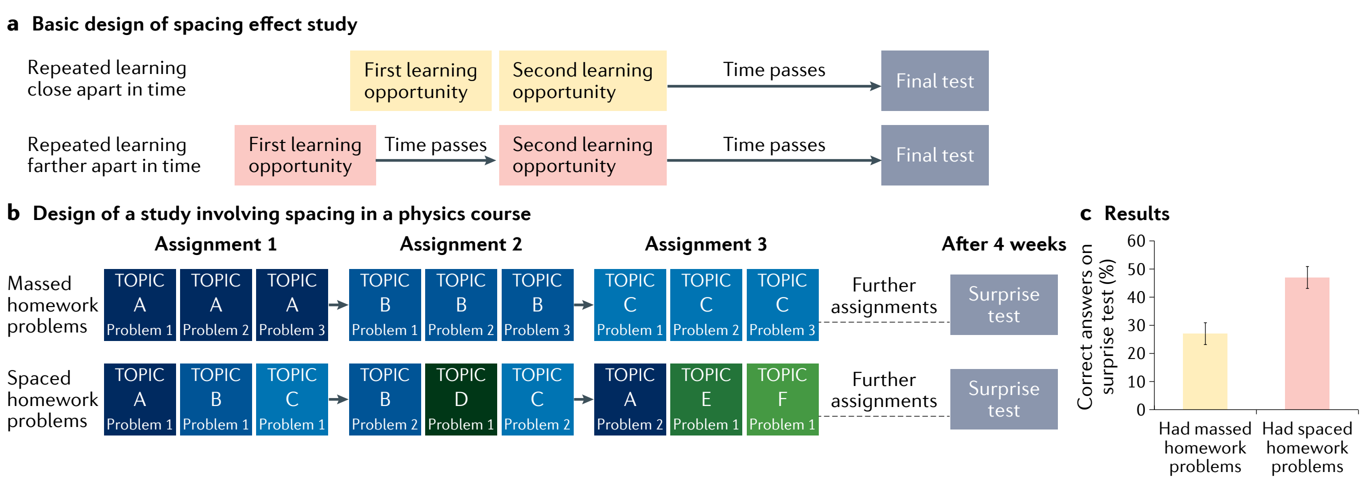

Fig. 2 | **The spacing effect. a** | In studies of the spacing effect, some learners complete multiple learning opportunities close together in time (top row), whereas other learners complete the same opportunities spaced farther apart in time (bottom row). After a set interval, learners are given a final test. **b** | In an undergraduate physics class, students learned about various topics and then completed three homework assignments per week[21]. Homework assignments comprised either a single topic, such that students worked through problems pertaining to a given topic on a single day in a massed fashion (top row), or different topics, such that students worked through problems pertaining to a given topic across different days in a spaced fashion (bottom row). **c** | Spaced homework assignments produced significantly better performance than massed homework on a transfer test (with novel problems) 4 weeks after the beginning of practice. Part **b** is adapted from REF.[65], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

learning in an undergraduate engineering course. Spaced quizzes led to better performance on the end of term examination in the same course and also on an examination 4 weeks later in a follow-up course[26]. Spacing benefits have been observed 35 days after learning for critical thinking[18], several weeks after learning for scientific knowledge and vocabulary[27,28], several months after learning for US history facts[29] and up to a year after learning for general knowledge facts[30].

According to theories of the spacing effect, the extra time between learning sessions could promote learning by providing a mental break that encourages more effective attention[31,32]. Spacing study sessions also creates distinct learning experiences with unique contextual features (such as the learning environment or the learner's subjective internal state) that can serve as memory cues[33,34]. Spaced study sessions increase the need for learners to retrieve information from earlier sessions[35,36], engaging the benefits of retrieval practice, as discussed in the next section. Finally, time-dependent neural consolidation processes might also contribute to the spacing effect[37]. These theoretical accounts are not mutually exclusive and the proposed processes might operate simultaneously.

Spacing benefits both memory retention and transfer. For example, spaced practice for the definitions of new vocabulary words benefits later retention of the meanings[38]. Spaced practice also builds near and far transfer proficiency. For example, spacing benefits application of mathematics procedures to new problems[16,19], application of a scientific principle from one domain to another[17], diagnoses of psychiatric disorders for new individuals[39] and proficiency of surgical skills in new situations[23].

Although spacing is beneficial across a range of learning activities, there is no universal ideal spacing schedule. Longer spacing schedules can be beneficial after information is already well learned and must be retained over a long delay[30]. However, longer spacing schedules can be less effective when information is not yet well learned, probably because of learners forgetting the information across sessions[40,41]. Because spacing increases the risk of forgetting between learning sessions, spaced learning activities should provide sufficient practice with the material to permit any forgotten information to be relearned. Although it is not possible to anticipate the perfect spacing schedule, effective spacing schedules typically involve providing sufficient practice with the learning material during the learning sessions and enough time between sessions such that the information is still familiar but not fresh in the mind. This situation creates the need to retrieve the previous learning experience during each practice session, engaging the beneficial effects of retrieval (which we discuss in the next section). Illustrating a range of effective spacing schedules, classroom studies have observed benefits of engaging learning activities (for example, practising to recall or apply information being learned) that are spaced apart by anywhere from 1 to 7 days[16,17,28,42].

Retrieving information from memory. A second effective learning strategy involves memory retrieval. Bringing memories back from long-term storage into conscious awareness is frequently thought of as occurring after learning is complete, in order to remember something that was learned previously. As such, it might seem counter-intuitive to regard retrieval as part of the learning process. However, it is possible to deliberately engage in the retrieval of memories while learning new information. For example, rather than reading a textbook chapter multiple times, one can read the chapter first, set it aside and then attempt to recall its contents from memory. Retrieval practice can take many forms, including completing practice tests, quizzing with flashcards or open-ended writing of remembered information.

When compared with study strategies that do not involve recalling information, retrieval practice typically generates more durable and accessible memories. This finding — called the retrieval practice effect or the testing effect — has been demonstrated in more than 200 studies from over a century of research[7,43–45] and is also regarded as one of the most robust findings in the psychology of learning (TABLE 2). Multiple meta-analyses confirm that the benefits of memory retrieval are robust, with effect sizes of Hedges' $g = 0.50–0.63$ for memory retention[4,45] and comparable effect sizes for transfer[7,46]. Retrieval practice benefits learning across the lifespan, in individuals ranging from 18 months old[47,48] to well over 60 years old[49].

In a typical study on retrieval practice, learners first have an opportunity to study, read or otherwise learn some information (FIG. 3a). Next, that information is learned again using one of two approaches. One approach involves restudying, re-reading or another strategy that does not involve memory retrieval. In the other approach, learners attempt to retrieve the material. After a period of time, learning is assessed. Typically, learners who used retrieval practice are better able to remember the information than those who did not. A single session of retrieval practice can generate memory improvements that persist for 9 months[29], and the positive effects of retrieval over multiple sessions can last for at least 8 years[50,51].

In some studies, learners have the opportunity to check whether they recalled information accurately after retrieval practice. For instance, they might view the correct answers or revisit the original learning materials. These feedback opportunities[52] typically increase the effectiveness of retrieval practice[45,53,54]. Learners who use retrieval practice followed by feedback typically perform even better on subsequent assessments than those who use retrieval practice alone. The improvement is likely to stem from instances when learners have difficulty retrieving accurate or complete information; feedback can be crucial to help correct inaccuracies and fill in knowledge gaps[45,55].

Research conducted in school-based settings confirms the value of retrieval practice during learning. In one study, third-grade students (8–10 years old) read an educational text about the Sun, then read the text a second time (the restudy group) or recalled key facts from the text by taking a fill-in-the-blank practice test (the retrieval practice group)[56]. A week later, the restudy group performed poorly on a test, with an average score of 53%. The retrieval practice group performed substantially better, with an average score of 87% (an effect

Table 2 | **Selected studies showing significant effects of retrieval practice across the lifespan**

Learner level	Learning materials	Implementation of retrieval practice	Ref.
Preschool or younger (<5 years old)	Picture names	Cued recall test followed by restudy or immediate answer feedback	188
	Toy names	Verbal cued recall test	189
	Video demonstrations	Re-enactment of demonstrated behaviours	47
Elementary school (5–10 years old)	Educational texts	Fill-in-the-blank test	56
	Map features	Map-based cued recall test with feedback	190
	Picture names	Verbal free recall test followed by restudy	191
	Spelling words	Cued recall test with feedback	58
	Symbols	Cued recall test with feedback	192
	Word lists	Word stem-completion test	193
Middle school (11–13 years old)	Botanical features	Cued recall test involving filling in a diagram	78
	Definition–word pairs	Cued recall test with feedback	194
	Educational texts	Free recall test	195
	Foreign language translations	Cued recall test with feedback	194
	History facts	Cued recall test with feedback	29
	Science course materials	Multiple-choice clicker test with feedback	196
High school (14–18 years old)	Educational texts	Multiple-choice and short answer test	197
	History course materials	Multiple-choice and short answer clicker test with feedback	59
	Mathematical facts, procedures	Short answer tests followed by restudy	198
	Science and history facts	Multiple-choice test	199
	Science concepts	Multiple-choice and true–false tests	200
	Word lists	Recognition test during verbal shadowing task	78
Undergraduate	Anatomy terms	Short answer test with or without feedback	201
	Biology course	Multiple-choice clicker quizzes with feedback	62
	Biology facts	Short answer test with feedback	202
	Biology processes	Short answer test with feedback	53
	Chemical engineering problems	Scenario-based problem-solving practice test	203
	Deductive inferences	Fill-in-the-blank or free recall test with feedback	66
	Educational texts	Short answer test with feedback	67
	Face–name pairs	Cued recall test	173
	Foreign language translations	Oral cued recall with feedback	204
	History facts	Short answer or multiple-choice test with feedback	202
	Map features	Map-based covert cued recall test with feedback	205
	Map locations	Virtual judgement of relative direction test with or without feedback	206
	Mathematical functions	Function estimation test with feedback	207
	Natural categories	Verbal cued recall test with or without feedback	208
	Neuroscience course	Multiple-choice or short answer test with feedback	209
	Psychology course	Multiple-choice or short answer test with feedback	210
	Scientific method	Free recall test followed by restudy	211
	Spelling words	Cued recall test with feedback	212
	Symbols	Cued recall test	213
	Word lists	Free recall test	214
	Word pairs	Cued recall test with feedback	215
	Word triplets	Cued recall test with feedback	216
	Video lectures	Multiple-choice or short answer test with or without feedback	217

Table 2 (cont.) | **Selected studies showing significant effects of retrieval practice across the lifespan**

Learner level	Learning materials	Implementation of retrieval practice	Ref.
Postgraduate	Anatomy and physiology	Free recall test followed by restudy	218
	Cardiac resuscitation	Physical practice test involving simulated cardiac arrest scenario	219
	Dental abnormalities	Multiple-choice test with feedback	220
	Neurological conditions	Short answer test with feedback	65
	Orthodontics procedures	Clinical scenario test with feedback	221
Older adults (>50 years old)	Face–name pairs	Oral cued recall test with feedback	222
	Prose passages	Multiple-choice test	223
	Scene images	Recognition test	224
	Word pairs	Cued recall test with feedback	49

size of Cohen's $d = 2.87$). Retrieval practice determined whether students acquired relatively limited or more comprehensive knowledge of the text.

Other studies exemplify the benefit of retrieval practice across a wide range of educational contexts, at different academic levels and with many subjects. For instance, in a study of word spelling, first to third-grade students in the United States (6–8 years old) consistently learned difficult spelling words more effectively after taking practice tests with feedback than after repeatedly copying correctly spelled words[57,58]. In some cases, the improvement in spelling scores after the use of retrieval practice was more than twice that of copying. Classroom studies at the middle school and high school levels (students aged 11–16 years and older) show consistent benefits of quizzes — conducted online, using paper and pencil or via audience response systems — over restudying for biology and history materials[59,60]. In those studies, retrieval practice typically improved unit and end of semester examination scores by a full letter grade (approximately 10%). Similar results have been reported for the use of retrieval practice in university-level biochemistry[61], physiology[62], psychology[63] and statistics courses[64].

Retrieval practice can also enhance learning at the postgraduate level. In one study, first-year medical students learned about four neurological conditions and then studied review sheets or took short answer practice tests before further studying (the latter constituting a retrieval practice with feedback condition)[65] (FIG. 3b). They repeated this procedure across four consecutive weeks. Six months later, when asked to propose treatments for new clinical scenarios, the students recalled relevant information more accurately and proposed more appropriate treatments for conditions that they had learned using retrieval practice than from studying only (effect size of Cohen's $d > 0.70$) (FIG. 3c).

Retrieval practice can be successfully implemented in many ways, including with free recall[66], multiple-choice[59], short answer[67] and true–false[68] quizzes or tests, as well as with online learning platforms[69], virtual flashcard programs[70] and audience response systems[62]. Even more esoteric methods of practising retrieval, such as playing games that incorporate memory retrieval[71] and mentally recalling information without producing an overt response[72], can also yield learning benefits. In most cases, the benefits of retrieval practice have been demonstrated by comparison to relatively passive strategies such as restudying, re-reading or copying information[45]. However, advantages of retrieval practice have also been observed against such active learning strategies as note-taking[73] and concept mapping[74]. Combining retrieval practice with learning activities that require the generation of new content[75,76], such as thinking of examples, can yield even greater learning benefits than simple retrieval alone[77].

According to theories of retrieval practice, there are multiple ways in which retrieval might promote learning. By one account, retrieval practice is beneficial because other learning methods do not involve retrieval, whereas all tests — and virtually all situations that require using previously learned knowledge or skills — do. Hence, there is a benefit to performing retrieval both when one is learning or studying and at a later test[78]. Alternatively, learners might remember contextual aspects of the information to be learned during retrieval practice that help them retain it[79]. By yet another account, the retrieval process might involve recall of not only correct information but also other information (for example, a learner's prior knowledge or thoughts) that helps to serve as memory cues for the learned information at a later test[80,81]. The act of retrieval could also create a new memory for the retrieval experience that is distinct from the memory of initially encountering the information[82], or might increase the number of neural pathways that can be used to access correct information[83]. Finally, retrieval practice could indirectly benefit learning by revealing what learners do and do not know[84,85], and therefore help them make effective use of feedback. These theories are not mutually exclusive, and more than one of these processes is likely to operate in a given learning situation.

Retrieval practice benefits memory retention and transfer when knowledge must be used in a similar way to how it was learned (near transfer)[46,86,87]. However, findings have been mixed in situations approaching far transfer. For example, some studies show that retrieval practice for deductive reasoning problems does not necessarily enhance the ability to draw inferences from individual premises that were studied[88], but engaging in multiple rounds of retrieval practice benefits both memory for the premises and the ability to draw inferences from them[66,89]. In the domain of procedural problem-solving, novice learners typically acquire and apply solutions to new problems better if they study fully

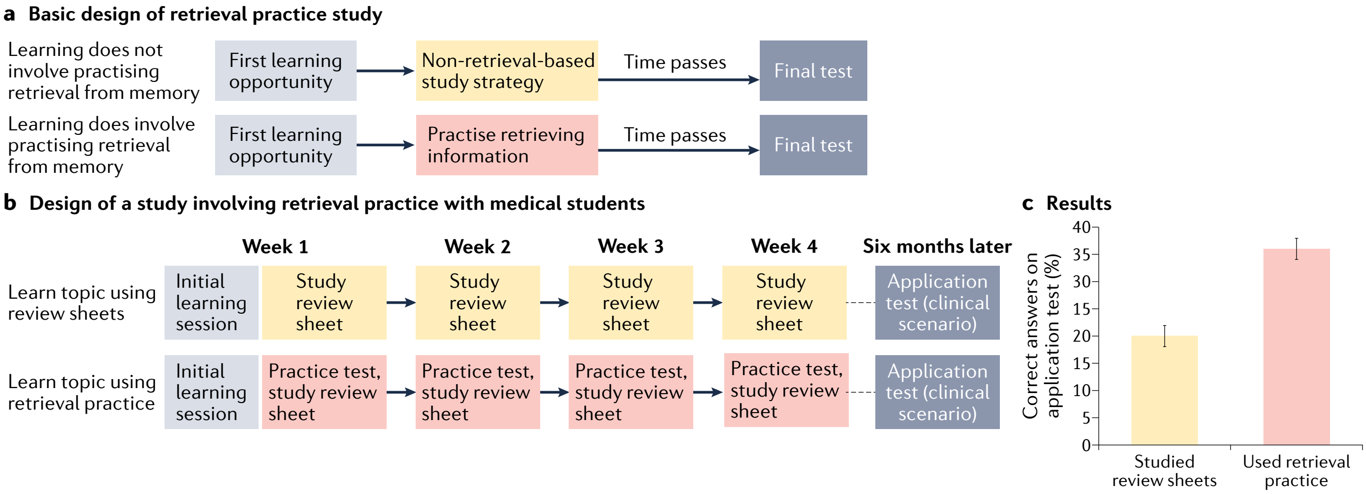

Fig. 3 | **The retrieval practice effect. a** | In retrieval practice studies, learners are first given an opportunity to learn some material and then have an opportunity to review that material. This review consists of viewing or re-reading the same material again (upper row) or trying to retrieve that material from memory (bottom row). **b** | Design of a retrieval practice study with medical students[65]. For each of four neurology topics, students first experienced an initial learning session. At the end of that session and during three more sessions over the next 3 weeks, they studied a review sheet (top row) or performed retrieval practice before studying the review sheet (bottom row). **c** | Students showed better performance for topics that had been learned using retrieval practice than only review sheet practice on a clinical application test (which assesses transfer of learning) administered 6 months later. Part **b** adapted with permission from REF.[65], Wiley.

worked examples without engaging in any retrieval, as opposed to using retrieval practice by attempting to solve problems on their own[90,91]. However, when learners practise repeatedly retrieving the same problem scenario and the steps required to successfully solve it, memory for solution procedures and the ability to solve similar problems is improved[92].

Studies of analogical problem-solving directly target the ability to transfer a solution learned in one domain (for example, the strategy that a military general should take to avoid landmines while capturing a fortress) to a different domain (for example, the strategy that a surgeon should use to remove a tumour while avoiding damage to healthy tissue). Although one study found that retrieval practice did not facilitate solution transfer[93], a follow-up study found that retrieval practice enhanced memory for the solution and the ability to transfer it, but only when learners were told that the previous solution could be relevant[94]. Other research shows that when a hint is provided, retrieval-enhanced memory for a solution or procedure facilitates its transfer to a new domain[67]. Thus, although retrieval practice does not automatically enhance the ability to notice the relevance of, and decide to apply, information in a new situation, it can contribute to transfer by enhancing memory for information that is ultimately needed for transfer[12].

Retrieval practice is most likely to be effective if it entails genuine effortful attempts to recall information. In addition, retrieval is most beneficial when it is reasonably successful at bringing accurate and relevant information to mind (particularly important when no feedback is provided)[95,96]. Moreover, as discussed next, using retrieval practice across multiple sessions separated by several days or even weeks can generate even more potent and long-lasting learning than massed retrieval practice[97].

Combining spacing and retrieval. Spacing and retrieval practice can be combined to enhance learning more effectively than either strategy alone. Retrieving information repeatedly over spaced time intervals produces durable and long-lasting benefits to learning, compared with simply reviewing the information over the same time intervals[65,98]. Retrieving information over longer spacing intervals is also more effective than retrieving it after shorter spacing intervals[29,97,99].

The combined powers of retrieval and spacing form the method of successive relearning. First introduced four decades ago[100], successive relearning is becoming known as a straightforward and effective learning strategy, particularly for building retention of factual materials (for example, vocabulary terms and definitions)[101]. Successive relearning involves an initial session in which learners try to retrieve the information they are learning and then receive feedback to check their accuracy, repeating retrieval practice until they are able to recall all of the information to a predetermined criterion (for example, 100% correct). This initial session is followed by additional relearning sessions of retrieving the information followed by feedback until the information can be recalled again to the same criterion.

Long-term learning is best attained when relearning sessions are spaced apart in time[50,102]. For example, one study reported significant benefits when undergraduate students engaged in successive relearning of introductory psychology terms and definitions every few days, compared with engaging with the material the same number of times without trying to retrieve it[70]. Another study found that undergraduate students' examination grades in an upper-level biopsychology course were enhanced by more than a letter grade after engaging in successive relearning of course information every few days, compared with using their own methods of studying[103]. Although the benefits of successive relearning (compared with the same quantity of learning within a single session) might be reduced for the learning of skills such as application of mathematical procedures[104], the technique seems to be quite effective for enhancing memory retention of fairly straightforward factual information.

The power of successive relearning can be boosted by engaging in extra retrieval practice in the first session. In one study, undergraduate students practised recalling introductory psychology terms and definitions followed by feedback until they recalled each correctly either once or three times, and then engaged in three more relearning sessions in which they recalled each term correctly once[105] (FIG. 4). Although recalling each term correctly three times in the first session was harder and took more time, this extra work paid off. Information that had been recalled correctly three times in the first session was easier to recall again in all subsequent relearning sessions (FIG. 5) and more likely to be accurate on the first attempt than information that was only recalled once. Specifically, the items that received extra early retrieval practice were recalled on the first try about 15% better 2 days later in the first relearning session (an effect size of Cohen's $d = 0.63$), and an advantage of extra early retrieval practice persisted over the subsequent two relearning sessions 8 and 10 days later.

In summary, spacing and retrieval practice benefit learning in various domains across the lifespan. Retrieval practice is a learning activity, and spacing is a way of scheduling the timing of learning activities. Spacing benefits both retention and transfer of knowledge, whereas retrieval benefits retention but produces limited benefits on far transfer. Successive relearning combines the benefits of spacing and retrieval and boosts memory retention for factual information.

Metacognition of strategy use

The effective use of learning strategies such as spacing and retrieval depends on learners' metacognition: the ability to think about one's thinking and regulate decisions accordingly. Learning strategies can be counter-intuitive and require effort to plan and initiate. Given the fundamental importance of metacognition to many aspects of mental functioning, it is studied in various subfields within psychology (for example, cognitive, educational, developmental and clinical psychology). Although the lineage of research in many of these subfields can be traced to a common beginning[106], metacognition is now conceptualized somewhat differently across subfields[107,108]. We focus on perspectives from cognitive and educational psychology on the use of effective learning strategies and self-regulated learning. Broadly speaking, self-regulated learning refers to the cognitive, motivational and affective processes that enable learners to plan, monitor and adapt their learning, including metacognition. We conclude this section by discussing how metacognition can be improved, incorporating perspectives from both subfields.

Perspectives from cognitive psychology. Within cognitive psychology, metacognition of learning often includes awareness (also known as monitoring), or a learner's knowledge about their own learning, and regulation (also known as control), or the learner's decisions or actions. For example, a student's metacognition when studying for a French examination might include awareness that they know present-tense verb conjugations well, but less confidence about their knowledge of past-tense conjugations. As a consequence, the student might decide to focus their studying on past-tense conjugations.

The outcome of a learning experience depends on learners' understanding of their own learning (monitoring) and making the right study decisions (control), and therefore accurate metacognition is a critical element of effective learning. However, metacognition is often inaccurate. With regards to monitoring, when learners are asked to judge their confidence in their knowledge or to predict how well they will perform on a test, their judgements and predictions often exceed their actual performance. In a study involving memory for simple pictures, 89% of first-grade children (6–7 years old) predicted that they would successfully recall all of the pictures they were shown, but on the test they only recalled about half of the pictures[109]. Although metacognitive ability develops from childhood to adulthood[110,111], overconfidence occurs at all levels of education beginning in primary school, with students over-predicting their own performance on assessments and examinations in various subject areas[16,109,112–114].

Learners also often demonstrate poor metacognitive control and make suboptimal decisions during learning. Based on surveys of students' study behaviours, few students engage in spacing out their studying over time but, instead, tend to 'cram' their studying within a few days of an examination[115]. Although many students at all levels of education make use of practice testing in the form of flashcards and self-quizzing, most students report using these strategies to find out how well they

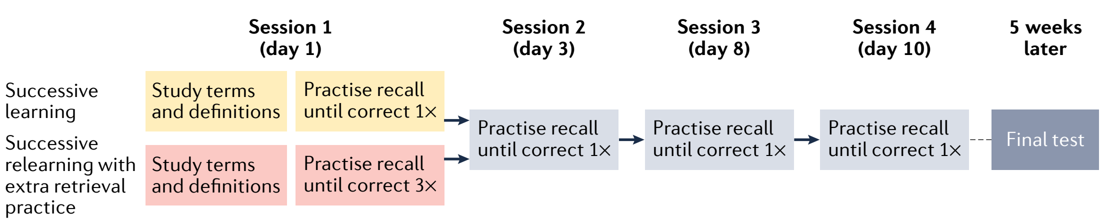

Fig. 4 | **Successive relearning paradigm.** In this example study, undergraduate psychology students practised recalling terms and definitions until they got each one right either once or three times[105]. Students then completed three additional relearning sessions every few days in which they practised recalling each definition again until they got it correct once.

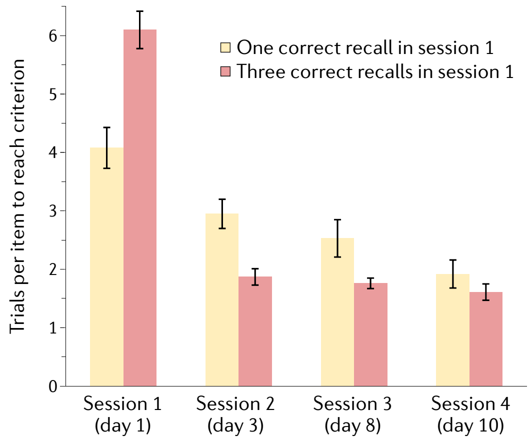

Fig. 5 | **Successive relearning results.** Results from the study depicted in FIG. 4 (REF.[105]). Recalling each term three times in the initial learning session resulted in increased efficiency in the subsequent relearning sessions. Copyright © 2011 by APA. Reproduced and adapted with permission from REF.[105].

know the information and not as a way of improving their learning, reflecting a lack of awareness of the direct benefits of retrieval practice[116–118]. Observational data on student behaviours in undergraduate courses also reflect underuse of spacing and retrieval strategies[119,120].

Faulty metacognition could arise from several different sources. One source is lack of knowledge about learning strategies. Indeed, students often lack knowledge about which learning strategies are effective[121,122] and seldom receive explicit instruction about how to learn effectively[123,124]. This instruction could be provided in schools, but teachers also often lack awareness of effective learning strategies[125]. At the K–12 level, teacher training often focuses on domain content and pedagogical content knowledge at the expense of domain general learning principles and strategies[126]. Higher education instructors receive little, if any, formal training on how to teach, let alone how to support learners in developing their ability to learn effectively. Another possible contributor to poor metacognition is the fact that common intuitions about learning tend to run counter to the way in which learning actually works (BOX 1).

In summary, the cognitive psychology perspective on learning strategy use has primarily focused on the role of metacognition in enabling learners to monitor and control their cognitive processes. We now turn to describing the educational psychology perspective, which also includes metacognition as a central component but conceptualizes strategy use within a broader set of cognitive, motivational and affective processes.

Perspectives from educational psychology. Within educational psychology, the interactions between metacognitive awareness and learning strategy use are situated within the broader concept of self-regulated learning[127,128]. From this perspective, self-regulated learning is a complex, multidimensional process that involves setting goals, planning, self-motivating, monitoring learning and self-reflecting, among other elements[129,130]. Learners might be self-regulating consciously or unconsciously, more effectively or less effectively, but are always engaging in some form of self-regulation while learning. Strategy planning and use is central to this larger process, which in real-world learning situations can be complicated by numerous factors (FIG. 6). The understanding of when and how to use different strategies is critical because the optimal implementation of a given strategy can vary across contexts[131]. That is, the same general strategy can be used in different ways. Factors such as the nature of the materials to be learned (for example, domain, type or complexity), the nature of the learning activity (for example, reading a textbook or watching an educational video) and the assessment (for example, taking a multiple-choice examination or writing an essay) need to be considered when planning the use of learning strategies. Effective high-level planning for learning can be compromised if learners do not take all of these factors into account or if they forego a plan entirely.

Furthermore, as learners carry out any plan, they must monitor their progress towards their goals by regularly making metacognitive judgements about the past, present and future state of their learning[132,133]. Such judgements might include considering how challenging it will be to learn a particular set of material, how well material has been learned already or the accuracy of the answers generated during their retrieval practice. The accuracy of these judgements directly informs the decisions that learners make in regulating their learning[134]. Such decisions include pivoting to a different learning strategy, allocating more study time to one set of material relative to another or deciding to terminate study. Inaccurate decisions can be costly, bringing additional motivational and affective elements into the metacognitive process.

The educational psychology perspective is quite useful for considering how cognitive and metacognitive processes interact with motivational and affective processes. Theories of self-regulated learning within this perspective include such components[129,135,136]. Indeed, much research in educational psychology has focused on how learners regulate their motivation to enhance their willingness and effort to engage in a learning task when faced with challenges such as boredom or difficulty[137,138]. Forging connections between educational and cognitive psychology around the motivational and affective aspects of learning strategy use is of increasing interest to researchers[115,117,139,140].

Although there is consensus among researchers about strategies that are effective for learning, there is little scientific knowledge about how to support learners in acquiring the metacognitive knowledge and skills needed to facilitate optimal strategy selection and use. According to the friction hypothesis, students naturally develop more effective strategies when they encounter challenges in their learning environments: experiencing challenges leads to growth in learning[141]. Although learners become more sophisticated in their ability to regulate their own learning as they develop and go through schooling, evidence to support the friction hypothesis is mixed at best[142–144]. It seems implausible that students could acquire the necessary complex mental model to guide effective learning without formal instruction to complement personal experience[145,146].

For example, despite the importance of tailoring learning plans to factors such as the nature of the test, little evidence indicates that learners adjust their plans to match the test in educational contexts[147], even though they sometimes do in laboratory contexts[148].

In sum, the educational psychology perspective complements the cognitive psychology perspective. The cognitive psychology perspective focuses on the micro-level aspects of metacognition that occur within a single learning episode, whereas the educational psychology perspective focuses on the macro-level aspects of metacognition that occur across learning episodes. Future work is needed to bridge these two perspectives and examine how micro-level cognitive processes operate within macro-level cognitive, motivational and affective processes across contexts. Uniting these two perspectives is critical to improving the metacognition of strategy planning and use.

Improving metacognition. Improving metacognition is a complex and challenging endeavour. From the cognitive psychology perspective, efforts to improve metacognition have focused on increasing learners' awareness and use of effective learning strategies. From an educational psychology perspective, improving metacognition is conceptualized within a broader set of cognitive, motivational and affective components, all of which are critical to effective strategy planning and use. Many learners have inaccurate beliefs about learning that could be resistant to change (BOX 1). The process of facilitating the acquisition of an accurate mental model of effective learning is therefore more likely to be a process of conceptual change[149] than of increasing the complexity of a generally accurate initial model[10].

Even after learners are made aware of effective learning strategies, they do not automatically endorse or use those strategies[150,151]. Although some studies show that students' awareness of their own knowledge can be improved by directly experiencing spacing[16] and retrieval practice[152], awareness alone is not enough to produce lasting changes in learners' beliefs and strategy use. Neither is simple experience with any strategy sufficient to change learners' behaviours[151]. Even if learners know how to use a strategy, they are not likely to use it unless they believe that the strategy works for them. However, comprehensive interventions that involve direct instruction about effective learning strategies, along with the opportunity for students to practise these strategies over time in their own courses, can be effective[153].

Indeed, a comprehensive approach is needed to address the multiple factors that inhibit the development of metacognitive skills. The knowledge, belief, commitment and planning framework[154] contains four evidence-based practical recommendations for educators who want to implement such an intervention at any level of education. First, the intervention should provide direct instruction about effective learning strategies and how to use them. Second, interventions should provide learners with experiences using those strategies (combined with knowledge of the outcomes) that can increase their knowledge of, and belief in, the effectiveness of those strategies. Third, interventions should support learners to create a plan for implementing effective strategies in their own learning. Finally, interventions should encourage learners to commit to their plan by reflecting on the benefits of using such strategies. The knowledge, belief, commitment and planning framework posits that all four components are necessary for an effective intervention. This multifaceted approach is critical to producing a mental model of effective learning that enables eventual independence as well as generalization to new learning experiences. Much like the acquisition of any skill, learning to learn effectively takes time, practice, effort and support.

Box 1 | **False beliefs about learning**

Learners hold numerous inaccurate beliefs about learning. These beliefs can be studied directly by collecting learners' opinions about the effectiveness of specific learning strategies. For example, when given a scenario describing spacing (compared with massing) and retrieval practice (compared with restudying) and asked which strategy would be more effective for learning, undergraduate students tend to choose the less effective strategies of massing and restudying[225]. Although spacing works for various learning materials, learners take into account the difficulty of the material and are more likely to prefer massing when they anticipate taking an easy test[150].

More broadly, the effort involved in a learning strategy might influence learners' beliefs about that strategy. Strategies such as repeatedly re-reading and highlighting tend to increase the feeling of fluency or ease with which materials are processed, and learners mistake this fluency as an indication that the materials have been well learned[132,226]. This 'illusion of learning' could be part of why students tend to overuse ineffective strategies[116,122,125,227] even though they are a poor predictor of academic success[228]. Students also endorse other situations that minimize the appearance of effort and difficulty — such as a lecture delivered in a smooth and well-polished manner or a lecture compared with active problem-solving activities — as more effective for their learning, although the opposite is true[132,226,229].

By contrast, effective learning strategies such as spacing and retrieval (along with other potentially effective strategies such as interleaving[230] and pre-questions[231]) involve effort and a greater likelihood of making errors. However, learners believe that strategies involving effort are less effective for learning[91]. Even after directly experiencing spacing and retrieval in their own learning, learners rated these strategies as less effective than massing and re-reading, respectively[232]. Learners also rated spacing and retrieval as more effortful, and ratings of effort negatively predicted perceived effectiveness of the strategies and willingness to use them. Thus, students tend to misinterpret effort as a sign of ineffective learning[232] or the inability to succeed[233]. This misperception matters because learners' beliefs about the effectiveness of strategies are related to the use of those strategies[117,234,235]. For instance, these false beliefs could underlie students' tendencies to avoid learning situations that involve effort[232] and errors[236].

False beliefs about learning could originate from various sources, including learners' intuitions, experiences and even formal education. Such beliefs are not easily and immediately changed through simple interventions such as a one-time demonstration of an effective learning strategy[39,170]. However, learners can acquire more accurate beliefs about learning through comprehensive interventions that involve direct instruction on the research supporting effective learning strategies and how to use them, combined with continued use of those strategies over time and experience with the outcomes[153].

Summary and future directions

Research on the psychology of learning has revealed that spacing and retrieval practice reliably enhance learning. However, these strategies are underused by students, possibly due to metacognitive factors such as false beliefs about learning, lack of awareness of effective learning strategies or the counter-intuitive nature of these strategies.

Successful learning requires an effective 'learning routine' — knowledge of the right strategies at the right times — as well as regular use of that routine. Learners

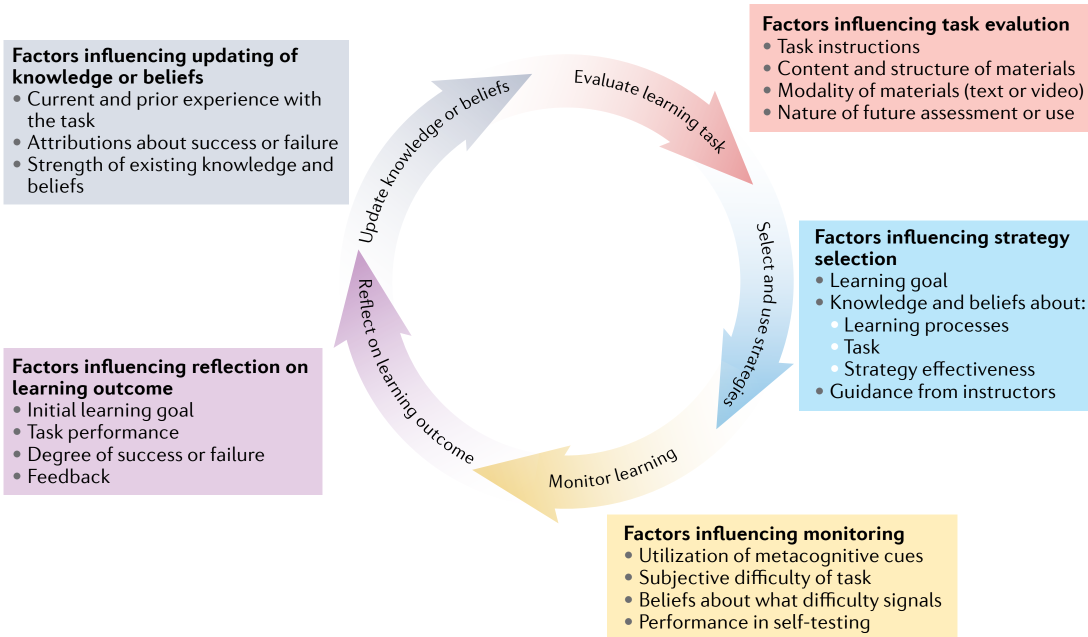

Fig. 6 | **Common factors influencing the metacognition of strategy use.** Metacognition of strategy use is conceptualized as a cyclical process influenced by various factors at each stage. The factors specified are not intended to be an exhaustive list (for example, learners' motivation and affect can influence strategy use at multiple stages) but are examples to illustrate the complex nature of the metacognitive processes involved in strategy use.

can be aware of what is needed for effective learning but fail to achieve their learning goals if they do not carry out an effective routine. Thus, a top priority for future research is to understand the decisions and actions that learners take during learning, including their use (or misuse) of effective learning strategies and the factors that hinder or facilitate use of these strategies. The motivational and affective influences on these decisions are particularly important in real learning situations, highlighting the need for more studies investigating how these factors contribute to learners' decisions and actions. Furthermore, future research can bring critical new insights by broadening the approach to understanding how complex mental models of learning are developed, through exploring the contributions of various cognitive and non-cognitive factors (including social, motivational and affective aspects) to self-regulated learning in real situations.

Technology is likely to play a key role in future research on learning. New technology makes it possible to collect large quantities of data quickly, opening up possibilities for the analysis of comprehensive datasets that include information about students (for example, demographic information and prior knowledge), their learning behaviours and decisions, and the learning context. For instance, online course management systems can collect data on the effectiveness of particular strategies (such as online quizzes) and student characteristics, which can together answer how course-related and student-related factors interact to predict learning. Technological advances also enable new research questions, such as determining the effectiveness of quizzes that are adapted to the learner's performance. Digital tools can also make it easier to implement learning activities and evaluate the effectiveness of learning strategies in ways that have not yet been widely and systematically explored, such as using mobile devices to deliver practice quizzes outside class[155].

Finally, an important question for future research is how to effectively enhance skills in critical thinking. In an age when information is widely available but not always accurate[156–159], one of the most valuable skills a learner can have is the ability to critically evaluate information. Effective learning strategies such as spacing can enhance skills in critical thinking and evaluating the credibility of information[18]. More research can shed additional light on the best strategies and approaches for building these skills. Critical thinking skills will be especially important for learners in an educational landscape that is becoming increasingly flexible and dependent upon learners to initiate and regulate the actions that are best for their own learning.

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