

OPINION

Current concepts in procedural consolidation

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Practice is vital to the acquisition of new skills, but the brain does not stop processing information when practice stops. After practice, changes take place that strengthen and modify the new skill. These changes, described under the umbrella term ‘consolidation’, take two distinct forms: the enhancement of skills and the stabilization of memories. Here we describe and evaluate the evidence for these types of consolidation.

The term consolidation was coined over one hundred years ago to describe the reduction in fragility of a declarative memory — a memory for a fact or event — after its encoding¹. Through consolidation, a new, initially fragile memory is transformed into a robust and stable memory. This fertile concept has guided important experimental work and provided an explanation for key features of the amnesiac syndrome². Given this success, it is not surprising that the concept of consolidation has been applied to other memory systems.

For procedural memories, which relate to the acquisition of a skill, consolidation can describe two different behavioural phenomena³. One is the ‘off-line’ improvement of skill that can occur between practice sessions; the other is the reduction in fragility of a memory trace after the acquisition of a novel skill (FIG. 1). These types of consolidation are not mutually exclusive, and might be complementary. But their behavioural properties and the criteria that must be satisfied to demonstrate their existence differ. Here we discuss the evidence for both types of

consolidation and suggest that, although there is convincing evidence for each type, there are inconsistencies that remain to be resolved. These stem, at least in part, from a poor understanding of the rules that guide procedural consolidation. We describe what these rules might be and suggest experimental approaches to testing these predictions.

Consolidation as off-line improvement
Consolidation can describe the skill improvements that occur between practice sessions (FIG. 1). These ‘off-line’ improvements occur without physical practice and often depend on sleep. For example, performance in a perceptual discrimination task increases by 15–20% after a night’s sleep^{4,5}. Similar overnight improvements are seen in the performance of short sequences of finger movements^{6–8}; only negligible improvements are seen when the same interval between sessions is spent awake. Learning a different sequence before sleep can block these improvements⁹, implying that overnight improvements are supported by an active and sequence-specific mechanism. Moreover, the overnight improvements are related to the amount of time spent in a particular component of sleep (for example, stage II non-rapid eye movement sleep⁷) or in combinations of sleep components^{10–12}. Being deprived of specific sleep components¹³, or of all sleep¹⁴, greatly reduces the overnight skill improvement. This reduction is not due to fatigue, because the effect persists even when the participants have recovered from sleep deprivation^{14,15}. Nor do circadian factors explain these improvements, because skill

enhancement does not depend on the time-of-day of testing or re-testing^{6,7,16}. Instead, these off-line improvements seem to be supported by marked changes in the neurophysiological properties of the brain that occur during sleep¹⁷.

During sleep, a day’s events seem to be replayed in the brain, and neuroplastic mechanisms are enhanced^{18–20}. For example, there are sleep-related changes in acetylcholine, a neuromodulator that is associated with neuroplasticity and learning^{21–23}. These changes make sleep ideally suited to refining and enhancing memories and skills. Overnight skill improvements are likely to be supported not only by a replay of past events but also by a reorganization of this information²⁴. This single process of reorganization could account for many sleep-dependent behavioural improvements, such as overnight improvements in perceptual discrimination, solving anagrams and other cognitive tasks^{6,7,14,24,25}. After sequence learning¹⁶ or finger tapping^{6–8}, overnight reorganization of the memory trace might lead to changes in the representation of finger movements that have previously only been associated with practice^{26–28}. However, these results should not be interpreted too broadly: it should not be assumed that all off-line improvements are sleep-dependent. Recent evidence and some classical observations suggest that time alone can sometimes support off-line learning.

Are there sleep-independent improvements?

Improvements are sleep-dependent when participants are asked to learn a sequence of finger movements^{6,7,16}. These skills are acquired intentionally (explicit learning) by participants. Skills can also be acquired unintentionally (implicit learning), and in this situation, off-line learning is not sleep-dependent¹⁶. Instead, similar improvements develop over the day (for example, from 8am to 8pm) and overnight (for example, from 8pm to 8am). These improvements cannot be attributed to practice at re-testing, because there is no demonstrated improvement with

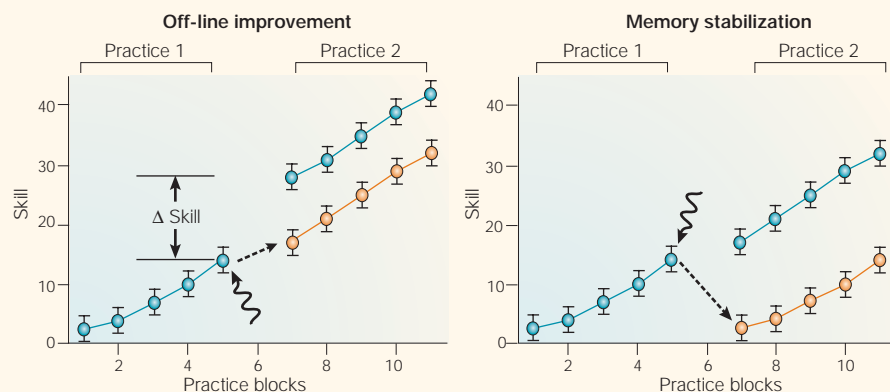


Figure 1 | The main features of two types of procedural consolidation. The left panel shows off-line learning. During practice (fast learning), there are considerable improvements in performance, whereas between practice sessions (slow learning), improvements can take several hours to emerge⁶¹. Disruption of off-line learning (lightning arrow) causes skill only to be retained (orange line). There is a slight skill improvement, even after disruption of this learning, because of the skill acquired during the first practice block of the second session (for detailed explanation, see FIG. 2). The right panel shows the behavioural features of memory stabilization. There is no between-session skill improvement, but disruption (lightning arrow) of the memory consolidation causes skill to return to a naive state (orange line).

only 15 min between testing and re-testing¹⁶; it takes at least 4 h between sessions for off-line improvements to appear²⁹. Two important features emerge from these studies: (1) an individual's awareness of learning a new skill is an important factor in off-line learning; and (2) off-line learning is not exclusively sleep-dependent, but can also be time-dependent.

Classical studies also indicate that time-dependent skill improvements are not limited to sequence learning. In the rotary pursuit task, a participant holds a stylus on a rotating target for as long as possible. The time on target steadily increases with practice, and when subjects are re-tested after a 15-min rest, performance has greatly improved³⁰. The dominant explanation for this improvement has been the passive dissipation of fatigue³⁰. According to this explanation, fatigue accumulates during initial testing and impairs performance. With rest, fatigue dissipates and allows the skill acquired to be fully expressed during re-testing. However, this between-session improvement can be blocked by learning another version of the rotary pursuit task³¹. This indicates that an active mechanism might underlie the skill improvements, and that this active process can be blocked by an interference task. Nonetheless, it is perhaps surprising that improvements in this task take only 15 min to develop, whereas other tasks require sleep to show similar improvements (for example, see REF. 7). Overall, the evidence is mixed for this off-line improvement being supported by active or passive mechanisms; selecting one over the other is probably based more on opinion than on evidence. Nonetheless, the rotary pursuit task suggests that time-dependent skill

improvements might be a property, not only of implicit sequence learning, but also of other procedural tasks.

Are off-line improvements a common feature?

It would be premature to state that off-line skill improvements are a general motif of all procedural learning. Only a handful of procedural tasks have shown evidence of off-line learning^{4,6,7,14,16}. Two large and important categories of skill learning have not, as yet, convincingly shown off-line learning: kinematic adaptation and dynamic adaptation (BOX 1).

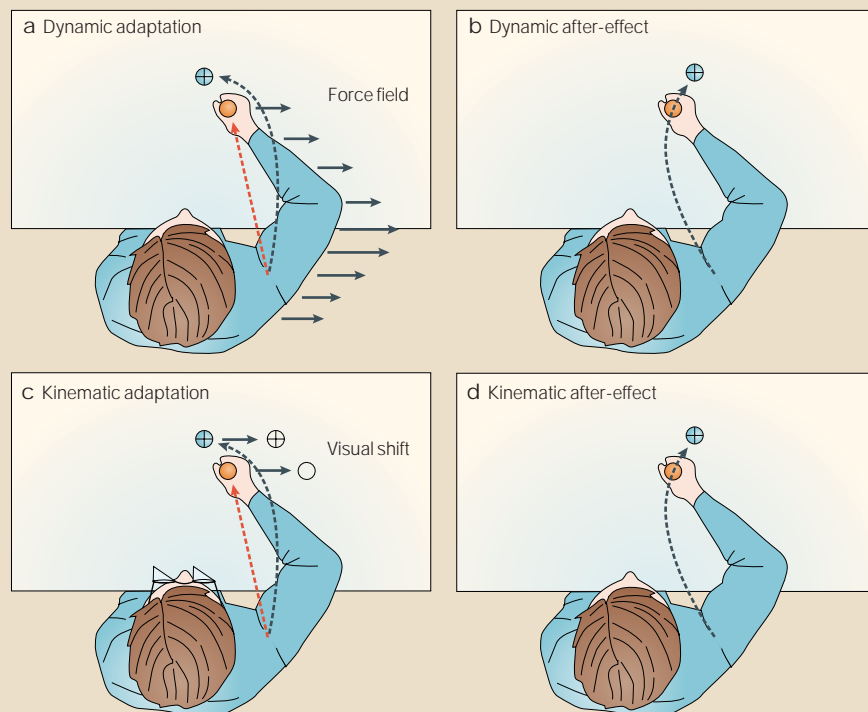
In dynamic adaptation tasks, participants modify their reaching movements to the presence of a force field. This field forces a participant's reaching movements off target. By contrast, distorted visual feedback, for example from wearing prism goggles, causes kinematic adaptation. Initially, the force-field or visual distortion causes reaching movements to be inaccurate. With practice, participants quickly adapt and produce accurate movements (for example, see REFS 32,33). The skill in making reaching movements in these novel environments does not increase between testing and re-testing sessions, even when the sessions are 24 h apart^{32,34,35}. Average skill at re-testing is substantially greater than during initial testing, but this should not be taken as an indication of off-line improvement (FIG. 2). To demonstrate off-line learning, it is necessary to eliminate the effects of practice during re-testing^{7,16}. This has not yet been done in kinematic or dynamic adaptation studies, because they were not designed to answer this type of question. Instead, most of these studies were designed to examine consolidation as the stabilization of procedural memories (see later).

An important test: saccadic adaptation. For off-line learning to be considered a general property of the procedural memory system, it is necessary to show between-session skill improvements in various tasks. Off-line motor skill learning, as opposed to perceptual learning, has only been demonstrated in manual tasks, none of which required either kinematic or dynamic adaptation. One procedural learning task that could give a powerful test of between-session skill improvements is saccadic adaptation³⁶. This type of kinematic adaptation requires an individual unconsciously to change the amplitude of their saccadic eye-movements. Off-line improvement of saccadic adaptation would provide evidence of procedural consolidation in the oculomotor system. Saccadic adaptation takes place outside a participant's awareness. Therefore, such an experiment would also be a good test of the principle suggested from sequence learning studies: that unconsciously acquired skills undergo time-dependent off-line learning, whereas consciously acquired skills undergo sleep-dependent off-line learning¹⁶. A practical difficulty would be to avoid de-adaptation of the saccades between testing sessions.

Summary. The improvement of skill without practice, which we call off-line learning, has been a robust finding across many laboratories and tasks. Whether off-line learning should be regarded as a general feature of motor learning is less certain, because several procedural tasks have yet to be tested for their capacity to exhibit off-line learning. Perhaps of greater interest is how different memory systems or processes (for example, implicit versus explicit memory) interact after skill acquisition, and how this interaction is modified by sleep. We suspect that the rules that guide off-line learning will emerge from an improved understanding of these and other interactions¹⁶.

Consolidation as memory stabilization Consolidation can also describe the reduction in fragility of a motor memory trace after encoding³⁷. A newly acquired skill can be lost if an individual immediately attempts to acquire skill in another task. However, if time passes between acquisition of the first skill and training in the second, the amount of interference decreases³⁷. This pattern is a robust feature of dynamic adaptation^{32,38,39} (BOX 1) that occurs with or without sleep³⁵ and has been interpreted as showing that exposure to a second procedural task disrupts the memory trace for the first task — a type of retroactive interference. As the time between the first and second task is lengthened,

Box 1 Dynamic and kinematic adaptation



Dynamic and kinematic adaptation are two widely studied examples of procedural learning. Both require participants to make reaching movements to a target (a, turquoise circle with a cross). In dynamic adaptation, a force field pushes a participant's reach off course, so that initial trajectories (a, black line) are curved. With practice, participants learn to adapt to the force field and to produce straight reaching movements (a, red line). To adapt to the force field, a new relationship between the motor command and the motion of the limb has to be learnt. By contrast, kinematic adaptation involves learning a new relationship between coordinate systems, such as the relationship between arm joint angles and observed hand position. Wearing prism goggles (as in c) can produce such a new relationship: there is a visual shift so that the hand and target positions (c, orange circle and turquoise circle with cross, respectively) are perceived at different locations (outlined circles). As participants learn this novel relationship, their reaching movements change from being curved (c, black line) to being straight (c, red line). In both procedural tasks, the extent of adaptation is measured as an after-effect (b and d). When the distortion is removed participants inappropriately compensate for it, making maladaptive curved reaching movements (b, d, black line): the greater the curvature, the greater the amount of prior adaptation. Neither of these tasks has shown off-line improvements.

In most studies, however, the difference between B and A_2 is substantial, and would be expected to cause significant proactive interference.

The neural mechanism through which interference prevents individuals from adapting their reaching movements to one and then another novel dynamic environment in quick succession is not known^{32,39}. However, it seems likely that the interference has a retroactive source, because it diminishes as the time between exposure to the first and second force field (A_1 to B) is increased. For example, participants can make accurate movements in both fields if exposure to them is separated by at least 6 h (REF. 39). By contrast, proactive interference should not be affected by this interval.

Unlike studies of dynamic adaptation, studies that involve kinematic adaptation (BOX 1) or finger-movement sequences find that the interference between two tasks does not diminish with time^{37,40}. The constancy of the interference effect does not show that its source is exclusively proactive: a retroactive component could be hidden by the proactive interference. However, any latent retroactive interference between kinematic adaptation tasks or sequence learning tasks would be substantially smaller than any proactive interference. Furthermore, proactive interference can account for most, if not all, of the interference between kinematic adaptation tasks^{33,40}. So far, there is no convincing evidence that skill acquired in kinematic adaptation tasks needs to undergo stabilization, and the evidence for sequence learning tasks requiring stabilization is mixed^{19,37}.

Future studies of interference between procedural learning tasks need to exclude proactive effects. One elegant way to control for proactive effects is to remove the second task altogether, and replace it with another type of interfering treatment. For example, applying transcranial magnetic stimulation (TMS) immediately after learning a new skill can establish whether a brain region makes a crucial contribution to an aspect of procedural consolidation^{41–43}. Assuming that TMS itself does not impair subsequent task performance, any impaired performance during re-testing must be due to retroactive interference from TMS on the original memory trace. Alternatively, giving individuals a drug after skill acquisition can affect a neuropharmacological system, allowing the importance of a particular neurotransmitter to be established³⁵. These approaches will potentially give insight into the biological systems and mechanisms that support the stabilization of procedural memories. They do, however, assume that the intervention has at most only a minimal effect on the retrieval of skill (that is, there is little proactive interference).

the memory trace of the first task is strengthened, and the disruptive influence of exposure to the second task is lessened. Two key behavioural criteria must be satisfied to show that a memory trace is stabilized after its encoding: (1) interference between tasks should be a consequence of the second task disrupting retention of skill in the first task (retroactive interference), rather than the second task impairing performance on the first task at re-testing (proactive interference); and (2) this retroactive interference should diminish as the time between testing and exposure to the second task is increased³⁷. Satisfying these criteria depends on the type of skill learnt, the variable used to measure skill, and the type of practice that guides skill acquisition.

Current issues in interference. Studies that explore the stabilization of procedural memories have a common design: participants practice on a task (A_1 , test) that requires adaptation of their reaching movements to a distorted environment, then switch to a second task (B), and then return to the original task (A_2 , or re-test). The participants' performance at re-testing (A_2) is compared with their performance during initial exposure (A_1). Impaired performance at re-testing implies that the memory of task A_1 was affected by retroactive interference from task B (FIG. 3). There is also possible proactive interference from task B onto A_2 , which is related to the difference between tasks B and A_2 . A slight difference should cause only minimal performance impairment.

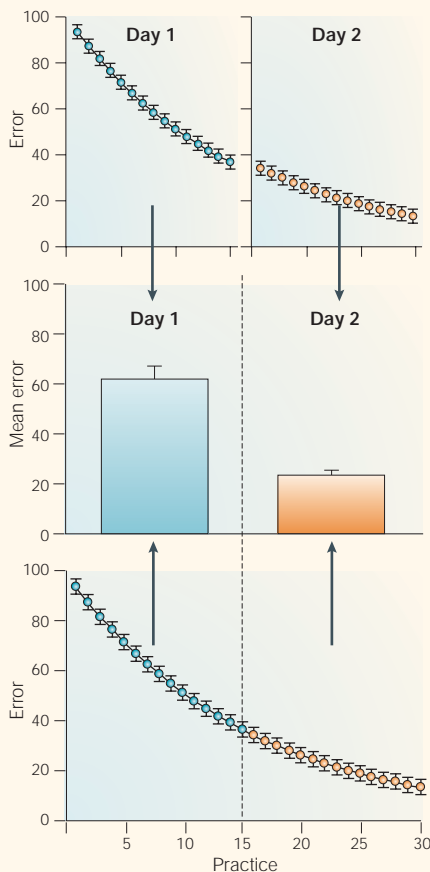


Figure 2 | Off-line learning and the effects of practice. Practice in a novel procedural task leads to a reduction in error. These reductions can take place over several days. The average error at re-testing (Day 2) would then be substantially less than the average error at testing (Day 1). If the testing and re-testing sessions were combined into one single practice session, and the average error of the first half of practice ('testing' session) were compared with the second ('re-testing' session), a substantial difference would emerge. This reduction, however, did not take place 'off-line' and can be accounted for by the effects of practice. Experiments should carefully exclude practice as a source of skill improvement (for example, see REF. 7).

Two recent studies have shown that TMS over the primary motor cortex (M1) can impair performance at re-testing of a simple, ballistic finger pinch movement^{41,43}. Both criteria for the stabilization of a memory trace were satisfied in these studies: there was retroactive interference, and it diminished with time. By contrast, performance in a dynamic adaptation task was not impaired following TMS over M1 (REF. 43). There are three possible explanations for these results. Different brain areas might support the stabilization of different skills; so M1 might be crucial only for the stabilization of certain skills. Alternatively, only certain aspects of a

skill might require stabilization; one of these two studies measured the acceleration of finger movements whereas the other measured accuracy^{41,43}. Finally, only certain types of skill might require stabilization. This is consistent with the notion that skills learnt during dynamic adaptation require stabilization^{32,39}, whereas skills acquired during kinematic adaptation or sequence learning do not^{33,37,40}.

Interference sometimes but not always. It is important to distinguish between a possible proactive or retroactive source of interference. However, emphasizing this distinction could lead to the mistaken impression that there is always interference of some form between procedural tasks. Although kinematic tasks often prevent skilled performance in dynamic tasks, the reverse is not true. Dynamic tasks can either prevent or enhance skilled performance in kinematic tasks^{44,45}. Skill enhancement, rather than interference, between two procedural tasks is a fairly common finding. Improved performance in a task can occur when participants have previously acquired skill in another task. Unlike off-line learning, these skill enhancements do not require an interval of time or sleep for their development (for example, REFS 6,7,16). Instead, skill enhancement in one task can occur when it is immediately preceded by practice in another task. These juxtaposed tasks can be similar; for example, skill enhancement is seen between different types of kinematic adaptation⁴⁶. But the tasks can also be very different; for example, there can be skill enhancement between prism adaptation and sequence learning⁴⁷. This enhancement is nonspecific; response times to both sequential and random trials are facilitated during sequence learning. By contrast, off-line learning facilitates the responses for the sequential trials but not the random trials⁴⁶. The enhancement between juxtaposed tasks might result from participants developing a better strategy for detecting patterns and errors, producing an improved learning capacity⁴⁷. Regardless of the mechanism that supports such skill enhancements, these studies show that interference between procedural learning tasks is not universal.

Different types of practice. Acquiring several skills simultaneously, or in quick succession, should not be possible because there is only a limited capacity for the retention of newly acquired skills^{32,34}. Only once the memory trace of a freshly acquired skill has been stabilized can another skill be acquired. Otherwise, the fragile memory trace associated with the first skill would be disrupted with the acquisition of the second skill.

In turn, memory for the second skill would be disrupted when the interleaved design returned to the first skill. If procedural memories require stabilization, it should be impossible to learn two skills simultaneously, or to acquire several skills in an interleaved design. This assumes that the brain's limited capacity to retain new skills is exceeded by learning just two skills. Such an assumption might not be justified. It might be necessary for three or four skills to be learnt in quick succession before this capacity is exceeded. But by modifying the original theory so that the brain now has an essentially arbitrary capacity to retain fragile procedural memories, the theory no longer predicts interference between tasks. In fact the two key behavioural criteria to establish the need of a procedural memory to undergo stabilization would be nullified by this modification³⁷. Consequently, the notion of the brain having a limited capacity to retain fragile nascent procedural memories is a fundamental aspect of how contemporary theory describes the stabilization of these memories.

When practice in one task is interleaved with practice in another task, individuals can acquire skill in both tasks. When two sequences are interleaved amongst a series of random trials, response times to both sequences show a substantial advantage over the random trials⁴⁸. A similar interleaved design can also allow the acquisition of skilful reaching movements in multiple visuomotor environments⁴⁶. It is also possible for two sequences to be acquired simultaneously^{49–52}. An ability to acquire skill in two tasks either simultaneously or in quick succession shows that there is, at most, only minor interference between tasks. Whether this is because the brain has a greater than expected capacity to retain fragile memories or because these memories do not require stabilization is uncertain. Regardless, neither of these interpretations is consistent with consolidation theory³².

There is also a contradiction between the stabilization of procedural memories and the 'chunking' principle of sequence learning. A single sequence is initially learnt as several short segments or chunks. With continued practice, the chunks become concatenated together, so that eventually a seamless string of finger movements is produced⁵³. Acquiring a sequence of finger movements involves learning several chunks and eventually performing them as a single sequence. However, there is no time between the chunks for stabilization to occur, and therefore there should be interference among the chunks that prevents the whole sequence from being

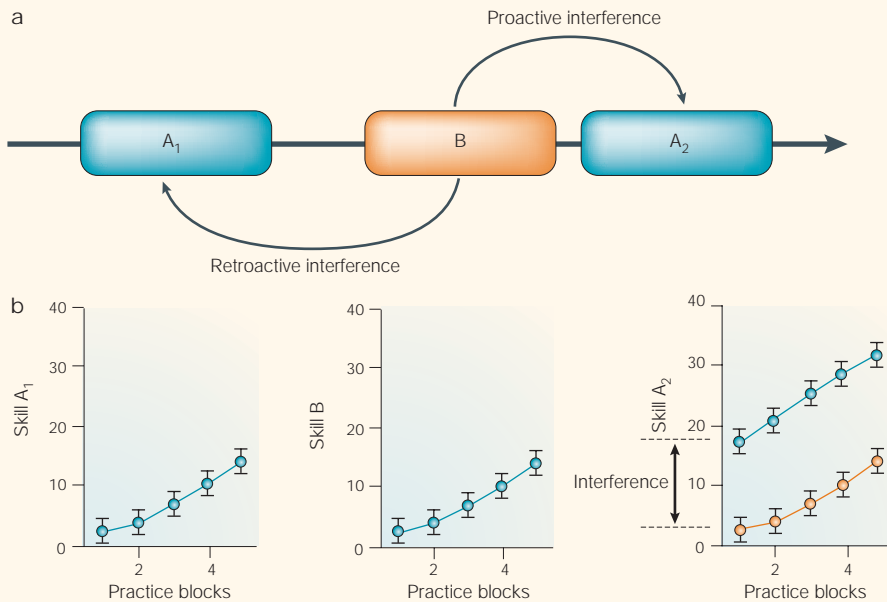


Figure 3 | Proactive and retroactive interference. Procedural learning in task B can cause skill in task A to be less at re-testing (A_2) than at initial testing (A_1) through two routes: it can disrupt the retention of skill in task A (retroactive interference) or it can impair performance at re-testing (proactive interference). Retroactive interference is responsible for disrupting the memory, whereas proactive interference is responsible for disrupting the retrieval of the memory. The lower panels show the skill improvements that would be expected during the performance of each of the tasks. Over five practice blocks, there are similar skill improvements in both task A and task B. When returning to task A, it might reasonably be expected that participants' skill (skill A_2) would be similar to the skill achieved at the end of the first practice (skill A_1). This is shown as a turquoise curve in the third graph. Contrary to this expectation, only a naive level of skill might be present, shown as the orange curve in the third graph. The interference responsible for this skill impairment can have either a proactive or a retroactive source.

learnt. A recent study showed that movement sequences are acquired through the concatenation of short chunks during random interleaved practice, but that during blocked practice concatenation does not occur⁵⁴. Perhaps the memory traces associated with each chunk fade too quickly, owing to instability, to allow concatenation. Consistent with this idea, skill retention is less after blocked practice than after random interleaved practice^{55,56}.

An exciting possibility is that the stability of a memory trace is related to the amount or type of practice (FIG. 4). For example, short, interleaved practice sessions might produce a stable memory trace that is not susceptible to interference. By contrast, prolonged practice might generate a less stable memory trace that does require consolidation. Individuals can adapt to two conflicting force fields if they are interleaved in a random fashion⁵⁷, but not if they alternate strictly or are presented in alternating blocks^{32,39}. There might also be a potential benefit of interleaved practice when acquiring multiple finger movement sequences. Short finger-tapping sequences that are only five items long seem to require stabilization⁹, whereas twelve-item sequences do not³⁷. Acquiring the twelve-item sequence

might be equivalent to learning two short sequences in an interleaved design. Consequently, the memory trace associated with this type of learning would be less fragile³⁷ than that for a single five-item sequence that was learnt in a block of practice⁹. Whether interleaved practice also has an advantage for kinematic adaptation is difficult to discern because there is, at most, minimal interference even with blocked practice. Consequently, whether the benefits of interleaved over blocked learning are a general feature of procedural learning is uncertain. Future studies should perhaps vary the type of practice and determine how this influences the stability of a procedural memory trace by measuring the amount of retroactive interference between two skills.

Each time a memory is retrieved it is thought to become fragile⁵⁸, and to require

time to become stable once again. The process of reconsolidation might occur in dynamic adaptation³⁵ and has been shown to occur in a finger-tapping task⁹. Reconsolidation might underlie the advantage of interleaved over blocked practice. Interleaved practice calls for multiple episodes of retrieval and this presumably gives multiple opportunities for stabilizing the memory trace^{59,60}. By contrast, there is only a single episode of retrieval and a single opportunity for stabilizing a memory in blocked practice. The greater opportunity for stabilization in interleaved practice might give rise to procedural memories that are less fragile than those acquired during blocked practice.

Summary. Interference between tasks, the identification of this interference as retroactive, and the reduction of this interference with time, are key behavioural features of memory stabilization. These features have been convincingly demonstrated for dynamic adaptation tasks, but not for either kinematic adaptation or sequence learning tasks. It seems that skills acquired through dynamic adaptation require consolidation, whereas other skills, such as sequence learning, might not. The type of practice that is responsible for encoding a new skill also seems to influence the stability of a memory trace: blocked practice produces unstable memories that require consolidation, but repeatedly alternating between different skills produces stable memories that do not require stabilization. Finally, it would be premature to imagine that all aspects of a newly encoded skill require stabilization. The consolidation of ballistic and targeted finger movements has recently been shown to differ^{41,43}, so some components of a skilled action might require stabilization, while others might not.

Conclusion

Procedural consolidation is an umbrella term that is used to describe the processing of a memory trace after skill encoding. Two important components of consolidation are off-line learning and memory stabilization. Most reported off-line improvements are sleep-dependent, and in most studies,



Figure 4 | Blocked and interleaved practice. **a** | With blocked practice, only one task can be learnt. For example, skill in task A will be lost by practising task B. **b** | By contrast, random interleaved practice allows skill in all three tasks to be acquired.

participants are aware of acquiring a new skill. By contrast, when a skill is acquired unintentionally, off-line improvements seem to depend on time and not on sleep. The properties of off-line improvements — for example, whether they are sleep- or time-dependent — might depend on the interaction between different memory systems and how this interaction is modified by sleep. Off-line learning properties might also be related to the type of skill that is learnt. For instance, in contrast to sequence learning, neither kinematic nor dynamic adaptation have shown evidence of between-session skill improvements. This might be because these types of adaptation have eluded the attention of those interested in off-line learning, and consequently, studies have not been designed to detect these skill improvements. Alternatively, off-line learning might be a feature of only some skills. Distinguishing between these possibilities should be the topic of future studies.

After practice, procedural memories are thought to be unstable. These unstable memories should be lost when two skills are learnt in quick succession, and this retroactive interference should diminish as the time between performing the two tasks is increased. Neither of these is a consistent feature of procedural learning, indicating that memory stabilization is not required for all types of procedural learning. Instead, the stability of a procedural memory might be related to the type of skill that has been learnt, what aspect of performance has been improved, and the type of practice that has guided skill acquisition. There is convincing evidence for procedural memories undergoing stabilization after dynamic adaptation. When the skill is acquired through interleaved rather than blocked practice, these memories are less fragile and so do not seem to require stabilization. The type of practice and its influence on memory stability might explain why some tasks require stabilization and others do not. Regardless of the type of practice, there are some procedural memories — for example, those generated during kinematic adaptation — that do not seem to require stabilization. The reason why some, but not all, procedural memories require stabilization can only be speculated upon. It might be related to the types of variable that are encoded within a memory; and this might in turn explain why certain aspects of improved performance show a need for stabilization. We now face the challenge of uncovering those aspects of skill acquisition that are related to the stability of a memory.

Some skills, such as sequence learning, might undergo both off-line learning and stabilization; other skills, acquired through dynamic adaptation, seem only to require stabilization. Further skills, such as those acquired through kinematic adaptation, might not undergo either type of procedural consolidation. This could be alerting us to the possibility that there are other aspects of consolidation besides off-line learning and stabilization.

Following the encoding of a new skill, multiple processes are activated, each of which obeys its own set of rules. We have suggested what some of these rules might be and how they might be uncovered. The future holds the promise of not only a richer understanding of these rules, but also an appreciation of the neuroplastic mechanisms that support procedural consolidation in all its guises. A better understanding of these rules and mechanisms might help to lay the foundation for improved neurorehabilitation.

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- Lechner, H., Squire, L. & Byrne, J. 100 years of consolidation — remembering Muller and Pilzecker. *Learn. Mem.* **6**, 77–87 (1999).
- McGaugh, J. L. Memory — a century of consolidation. *Science* **287**, 248–251 (2000).
- Eysenck, H. & Frith, C. *Reminiscence, Motivation, and Personality* (Plenum, New York & London, 1977).
- Karni, A., Tanne, D., Rubenstein, B. S., Askenasy, J. J. & Sagi, D. Dependence on REM sleep of overnight improvement of a perceptual skill. *Science* **265**, 679–682 (1994).
- Stickgold, R., Hobson, J. A., Fosse, R. & Fosse, M. Sleep, learning, and dreams: off-line memory reprocessing. *Science* **294**, 1052–1057 (2001).
- Fischer, S., Hallschmid, M., Elsner, A. L. & Born, J. Sleep forms memory for finger skills. *Proc. Natl Acad. Sci. USA* **99**, 11987–11991 (2002).
- Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A. & Stickgold, R. Practice with sleep makes perfect: sleep-dependent motor skill learning. *Neuron* **35**, 205–211 (2002).
- Korman, M., Raz, N., Flash, T. & Karni, A. Multiple shifts in the representation of a motor sequence during the acquisition of skilled performance. *Proc. Natl Acad. Sci. USA* **100**, 12492–12497 (2003).
- Walker, M. P., Brakefield, T., Hobson, J. A. & Stickgold, R. Dissociable stages of human memory consolidation and reconsolidation. *Nature* **425**, 616–620 (2003).
- Giuditta, A. *et al.* The sequential hypothesis of the function of sleep. *Behav. Brain Res.* **69**, 157–166 (1995).
- Gais, S., Pilhal, W., Wagner, U. & Born, J. Early sleep triggers memory for early visual discrimination skills. *Nature Neurosci.* **3**, 1335–1339 (2000).
- Stickgold, R., Whidbee, D., Schirmer, B., Patel, V. & Hobson, J. A. Visual discrimination task improvement: a multi-step process occurring during sleep. *J. Cogn. Neurosci.* **12**, 246–254 (2000).
- Smith, C. & MacNeill, C. Impaired motor memory for a pursuit rotor task following Stage 2 sleep loss in college students. *J. Sleep Res.* **3**, 206–213 (1994).
- Stickgold, R., James, L. & Hobson, J. A. Visual discrimination learning requires sleep after training. *Nature Neurosci.* **3**, 1237–1238 (2000).
- Maquet, P., Schwartz, S., Passingham, R. & Frith, C. Sleep-related consolidation of a visuomotor skill: brain mechanisms as assessed by functional magnetic resonance imaging. *J. Neurosci.* **23**, 1432–1440 (2003).
- Robertson, E. M., Pascual-Leone, A. & Press, D. Z. Awareness modifies the skill-learning benefits of sleep. *Curr. Biol.* **14**, 208–212 (2004).
- Hobson, J. & Pace-Schott, E. The cognitive neuroscience of sleep: neuronal systems, consciousness and learning. *Nature Rev. Neurosci.* **3**, 679–693 (2002).
- Wilson, M. A. & McNaughton, B. L. Reactivation of hippocampal ensemble memories during sleep. *Science* **265**, 676–679 (1994).
- Lee, A. K. & Wilson, M. A. Memory of sequential experience in the hippocampus during slow wave sleep. *Neuron* **36**, 1183–1194 (2002).
- Steriade, M. & Timofeev, I. Neuronal plasticity in thalamocortical networks during sleep and waking oscillations. *Neuron* **37**, 563–576 (2003).
- Graves, L., Pack, A. & Abel, T. Sleep and memory: a molecular perspective. *Trends Neurosci.* **24**, 237–243 (2001).
- Gu, Q. Neuromodulatory transmitter systems in the cortex and their role in cortical plasticity. *Neuroscience* **111**, 815–835 (2002).
- Gu, Q. Contribution of acetylcholine to visual cortex plasticity. *Neurobiol. Learn. Mem.* **80**, 291–301 (2003).
- Wagner, U., Gais, S., Haider, H. & Born, J. Sleep inspires insight. *Nature* **427**, 352–355 (2004).
- Stickgold, R. & Walker, M. To sleep, perchance to gain creative insight? *Trends Cogn. Sci.* **8**, 191–192 (2004).
- Pascual-Leone, A., Grafman, J. & Hallett, M. Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science* **263**, 1287–1289 (1994).
- Karni, A. *et al.* Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* **377**, 155–158 (1995).
- Pascual-Leone, A. *et al.* Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *J. Neurophysiol.* **74**, 1037–1045 (1995).
- Press, D. Z., Robertson, E. M., Casement, M. & Pascual-Leone, A. Increasing skill without awareness or practice. *Soc. Neurosci. Abstr.* **29**, 443.5 (2003).
- Eysenck, H. A three-factor theory of reminiscence. *Br. J. Psychol.* **56**, 163–181 (1965).
- Rachman, S. & Grassi, J. Reminiscence, inhibition and consolidation. *Br. J. Psychol.* **56**, 157–162 (1965).
- Brashers-Krug, T., Shadmehr, R. & Bizzi, E. Consolidation in human motor memory. *Nature* **382**, 252 (1996).
- Miall, R., Jenkinson, N. & Kulkarni, K. Adaptation to rotated visual feedback: a re-examination of motor interference. *Exp. Brain Res.* **154**, 201–210 (2004).
- Krakauer, J., Ghilardi, M. & Ghez, C. Independent learning or internal models of kinematic and dynamic control of reaching. *Nature Neurosci.* **2**, 1026–1031 (1999).
- Donchin, O., Sawaki, L., Madupu, G., Cohen, L. G. & Shadmehr, R. Mechanisms influencing acquisition and recall of motor memories. *J. Neurophysiol.* **88**, 2114–2123 (2002).
- Hopp, J. & Fuchs, A. The characteristics and neuronal substrate of saccadic eye movement plasticity. *Prog. Neurobiol.* **72**, 27–53 (2004).
- Goedert, K. & Willingham, D. Patterns of interference in sequence learning and prism adaptation inconsistent with the consolidation hypothesis. *Learn. Mem.* **9**, 279–292 (2002).
- Shadmehr, R. & Holcomb, H. Neural correlates of motor memory consolidation. *Science* **277**, 821–825 (1997).
- Shadmehr, R. & Brashers-Krug, T. Functional stages in the formation of human long-term motor memory. *J. Neurosci.* **17**, 409–419 (1997).
- Abeles, S. & Bock, O. Mechanisms for sensorimotor adaptation to rotated visual input. *Exp. Brain Res.* **139**, 248–253 (2001).
- Muellbacher, W. *et al.* Early consolidation in human primary motor cortex. *Nature* **415**, 640–644 (2002).

42. Robertson, E. M., Theoret, H. & Pascual-Leone, A. Studies in cognition: the problems solved and created by transcranial magnetic stimulation. *J. Cogn. Neurosci.* **15**, 948–960 (2003).
43. Baraduc, P., Lang, N., Rothwell, J. & Wolpert, D. Consolidation of dynamic motor learning is not disrupted by rTMS of primary motor cortex. *Curr. Biol.* **14**, 252–256 (2004).
44. Tong, C., Wolpert, D. M. & Flanagan, J. R. Kinematics and dynamics are not represented independently in motor working memory: evidence from an interference study. *J. Neurosci.* **22**, 1108–1113 (2002).
45. Tong, C. & Flanagan, J. R. Task-specific internal models for kinematic transformations. *J. Neurophysiol.* **90**, 578–585 (2003).
46. Cunningham, H. & Welch, R. Multiple concurrent visual-motor mappings: implications for models of adaptation. *J. Exp. Psychol. Hum. Percept. Perform.* **20**, 987–999 (1994).
47. Seidler, R. Multiple motor learning experiences enhance motor adaptability. *J. Cogn. Neurosci.* **16**, 65–73 (2004).
48. Willingham, D. B., Salidis, J. & Gabrieli, J. D. Direct comparison of neural systems mediating conscious and unconscious skill learning. *J. Neurophysiol.* **88**, 1451–1460 (2002).
49. Mayr, U. Spatial attention and implicit sequence learning: evidence from independent learning of spatial and nonspatial sequences. *J. Exp. Psychol. Learn. Mem. Cogn.* **22**, 350–364 (1996).
50. Schmidtke, V. & Heuer, H. Task integration as a factor in secondary-task effects on sequence learning. *Psychol. Res.* **60**, 53–71 (1997).
51. Shin, J. & Ivry, R. Concurrent learning of temporal and spatial sequences. *J. Exp. Psychol. Learn. Mem. Cogn.* **28**, 445–457 (2002).
52. Aizenstein, H. J. *et al.* Regional brain activation during concurrent implicit and explicit sequence learning. *Cereb. Cortex* **14**, 199–208 (2004).
53. Sakai, K., Kitaguchi, K. & Hikosaka, O. Chunking during visuomotor sequence learning. *Exp. Brain Res.* **152**, 229–242 (2003).
54. Wright, D. L., Black, C. B., Immink, M. A., Brueckner, S. & Magnuson, C. Long-term motor programming improvements occur via concatenation of movement sequences during random but not during blocked practice. *J. Mot. Behav.* **36**, 39–50 (2004).
55. Shea, J. & Morgan, R. Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *J. Exp. Psychol. Hum. Learn. Mem.* **5**, 179–187 (1978).
56. Simon, D. & Bjork, R. Metacognition in motor learning. *J. Exp. Psychol. Learn. Mem. Cogn.* **27**, 907–912 (2001).
57. Osu, R., Hirai, S., Yoshioka, T. & Kawato, M. Random presentation enables subjects to adapt to two opposing forces on the hand. *Nature Neurosci.* **7**, 111–112 (2004).
58. Misanin, J. R., Miller, R. R. & Lewis, D. J. Retrograde amnesia produced by electroconvulsive shock after reactivation of a consolidated memory trace. *Science* **160**, 554–555 (1968).
59. Nader, K., Schafe, G. & LeDoux, J. The labile nature of consolidation theory. *Nature Rev. Neurosci.* **1**, 216–219 (2000).
60. Sara, S. Strengthening the shaky trace through retrieval. *Nature Rev. Neurosci.* **1**, 212–213 (2000).
61. Karni, A. The acquisition of perceptual and motor skills: a memory system in the adult human cortex. *Brain Res. Cogn. Brain Res.* **5**, 39–48 (1996).

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Competing interests statement

The authors declare that they have no competing financial interests.

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