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Implications of the declarative/procedural model for improving second language learning: The role of memory enhancement techniques

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Abstract

The declarative/procedural (DP) model posits that the learning, storage, and use of language critically depend on two learning and memory systems in the brain: declarative memory and procedural memory. Thus, on the basis of independent research on the memory systems, the model can generate specific and often novel predictions for language. Till now most such predictions and ensuing empirical work have been motivated by research on the neurocognition of the two memory systems. However, there is also a large literature on techniques that enhance learning and memory. The DP model provides a theoretical framework for predicting which techniques should extend to language learning, and in what circumstances they should apply. In order to lay the neurocognitive groundwork for these predictions, here we first summarize the neurocognitive fundamentals of the two memory systems and briefly lay out the resulting claims of the DP model for both first and second language. We then provide an overview of learning and memory enhancement techniques before focusing on two techniques – spaced repetition and retrieval practice – that have been linked to the memory systems. Next, we present specific predictions for how these techniques should enhance language learning, and review existing evidence, which suggests that they do indeed improve the learning of both first and second language. Finally, we discuss areas of future research and implications for second language pedagogy.

Keywords

declarative memory, declarative/procedural model, memory enhancement, procedural memory, retrieval practice, second language acquisition, spaced repetition, spacing effect, testing effect

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I Introduction

Not surprisingly, most research on language has focused on language alone. However, in evolution and development, new functions commonly piggyback upon previously-existing biological mechanisms. Since language must ultimately be rooted in biology, it is thus likely that this domain relies importantly on previously-existing neurobiological substrates, whether or not these have become further specialized for language.

The declarative/procedural (DP) model simply posits that language learning, storage, and use depend heavily on the declarative and procedural memory brain systems. After all, most if not all of language must be learned, and these appear to be the two most important learning and memory systems in the brain. Crucially, both systems are well-studied at many levels in both humans and non-human animals, leading to a wide range of independent predictions about language.

Whereas previous research on the DP model has focused on the neurocognitive correlates of the two memory systems and ensuing neurocognitive predictions for language, there is also a large literature on learning and memory enhancement techniques that have been linked to these systems. The DP model specifically predicts that such techniques should also apply to language learning, in particular ways based on how language depends on the two systems. Thus, the DP model provides a clear theoretical motivation for using these techniques to enhance language learning, including in second language acquisition (SLA), with specific predictions for where and how the techniques should apply.

In order to lay a neurocognitive foundation for the predictions of the DP model regarding memory enhancement techniques, here we first present a summary of the neurocognition of the two memory systems, then briefly lay out ensuing neurocognitive claims of the DP model for both first and second language (L1 and L2). Next, we provide an overview of techniques (i.e. interventions) that have been found to improve learning and memory, focusing on two techniques – spaced repetition (the spacing effect) and retrieval practice (the testing effect) – that have been linked to declarative memory, and, in the case of spacing, to procedural memory as well. We then present the DP model's predictions for these two techniques for the enhancement of language learning after which we summarize existing language evidence, which suggests that these two techniques do indeed improve aspects of both first and second language learning. Finally, we discuss implications for second language learning and teaching, and avenues for future study.

II Declarative and procedural memory: Neurocognitive fundamentals

Here, we briefly present the neurocognitive fundamentals of the two memory systems, while in the following section we summarize the language claims of the DP model based on these fundamentals. (For more comprehensive examinations of the memory systems, see, for example, Ashby et al., 2010; Doyon et al., 2009; Eichenbaum, 2012; Henke, 2010; Squire and Wixted, 2011; Ullman, 2004, 2016.)

The declarative memory system has traditionally been defined as the brain system that underlies explicit knowledge (i.e. knowledge that can be brought to conscious awareness). This system, which is well studied in both humans and non-human animals, is rooted in the hippocampus and other medial temporal lobe structures. These structures are critical for the learning and consolidation (stabilization) of new knowledge, which however eventually relies largely on neocortical regions, particularly in the temporal lobes. Other brain structures also play a role, such as frontal regions (Brodmann's areas 45 and 47) that underlie the recall of stored information. (Note that the declarative and procedural memory systems refer here to the entire neurocognitive systems involved in the learning, representation, and use of the relevant knowledge, not just to those portions underlying learning and consolidating new knowledge, which is how some researchers refer to the systems; see Ullman, 2004, 2016.) Although the declarative memory system has long been implicated in the learning of explicit knowledge of facts (semantic knowledge) and personally experienced events (episodic knowledge), it has now become clear that the system is quite flexible in what it can learn. Indeed, evidence suggests that it underlies a much broader range of information, including implicit (non-conscious) knowledge of various sorts (Chun, 2000; Henke, 2010; Ullman and Pullman, 2015). However, declarative memory appears to be the only long-term memory system that underlies explicit knowledge; thus, any knowledge that is explicit was likely learned in this memory system. More generally, the system may be specialized for learning and representing idiosyncratic (non-derivable) information and arbitrary associations. In fact, this system may be necessary for learning such information and associations. For example, dense amnesics with extensive medial temporal lobe damage such as patient H.M. are virtually unable to remember new arbitrary facts or events, or to create new associations, such as in paired-associate learning tasks (Squire and Wixted, 2011). Information in declarative memory can be learned rapidly, even from a single exposure of a stimulus, although additional exposures (i.e. repetition) strengthen memories. Of particular interest for second language acquisition (see below), learning abilities in declarative memory seem to improve during childhood, then plateau in adolescence and early adulthood, after which they decline. Thus an older child or young adult tends to be better at learning in this system than a young child. (For reviews of declarative memory, see Eichenbaum, 2012; Henke, 2010; Squire and Wixted, 2011; Ullman, 2004, 2016).

Although procedural memory is less well understood than declarative memory, its neurocognitive correlates are becoming clearer (Ashby et al., 2010; Doyon et al., 2009; Ullman, 2004, 2016). This memory system, which underlies only implicit knowledge (i.e. knowledge not available to conscious awareness), depends on a network of interconnected brain structures rooted in frontal/basal-ganglia circuits. (Note that we use the term procedural memory to refer to a particular brain system and its characteristics; in contrast, some researchers use the term to refer to implicit memory more generally, across all memory systems that underlie implicit knowledge; see Ullman, 2016.) The system underlies the implicit learning and processing of a wide range of perceptual-motor and cognitive skills, including navigation, sequences, rules, and categories. The basal ganglia play a critical role in the learning and consolidation of new skills, whereas frontal (pre-) motor regions may be more important for processing skills after they have been automatized (Ashby et al., 2010; Doyon et al., 2009; Ullman, 2004, 2016). Learning in the system proceeds gradually through repeated exposure and is thus typically slower than learning in declarative memory, though what is eventually learned seems to be processed more rapidly and automatically than knowledge in declarative memory. Unlike declarative memory, learning and consolidation in procedural memory seem to be robust already early in life, though they may become somewhat attenuated during childhood and adolescence (Adi-Japha et al., 2014; Ullman, 2005).

The declarative and procedural memory systems interact in a number of ways (Packard, 2008; Poldrack and Packard, 2003; Ullman, 2004, 2016). Of particular interest here, the two systems can to some extent acquire the same or analogous knowledge or skills. Thus, importantly, they play at least partly redundant roles. Redundant knowledge seems to be acquired largely in parallel in the two systems. Perhaps not surprisingly, the nature of the knowledge learned in the two systems is often quite different, even while the knowledge in both systems may serve the same purpose. For example, evidence from rodents suggests that navigation in a maze (e.g. to find food) can be learned in procedural memory, such that animals learn to always turn in one direction, or in declarative memory, such that animals learn to turn towards a landmark, whichever direction it is positioned in.

Various factors appear to modulate which of the two systems is used for a given task or function that can be learned or processed by either system. The declarative memory system often acquires knowledge initially, thanks to its fast acquisition abilities, while, in parallel, the procedural system gradually learns analogous knowledge. This procedural knowledge is eventually processed rapidly and automatically, and often ultimately takes precedence over analogous declarative knowledge. Note that it is not the case that knowledge is in any sense 'transformed' from declarative to procedural memory. Rather the two systems seem to acquire knowledge essentially independently. Indeed, dense amnesics such as patient H.M. can learn in procedural memory in the absence of learning in declarative memory. Interestingly, the knowledge in declarative memory seems to remain intact even when procedural memory takes over. For example, lesions to procedural memory structures can lead to a reversion of dependence on knowledge that was initially learned in declarative memory (Packard, 2008).

The learning context can also affect which system is relied on more. Explicit instruction (e.g. regarding the order of items within a sequence to be learned in serial reaction time tasks) or even just paying attention to the stimuli and underlying rules or patterns (e.g. in probabilistic rule learning, such as in the 'weather prediction' task) can increase learning in declarative memory (Poldrack and Packard, 2003; Ullman, 2016). Conversely, a lack of explicit instruction, as well as manipulations that reduce attention to the stimuli (e.g. in dual task paradigms), or a high level of complexity of rules or patterns (reducing the learner's ability to explicitly detect them), may all shift learning towards procedural memory (Foerde et al., 2006; Ullman, 2016).

Many other factors likely also play roles affecting which system is relied on more. Any factor that enhances learning, retention, or retrieval in one of the memory systems more than the other should lead to an increased dependence on that system for those tasks and functions that can depend on either one. Thus, the relative functionality of the two systems can affect which one is relied on more. For example, likely due in part to a female advantage at declarative memory, females may rely more on this system, and males correspondingly more on procedural memory, for tasks that can be carried out by either system (Ullman et al., 2008). More importantly for our present purposes, the improvement of declarative memory during childhood, and the apparent attenuation of procedural memory over about the same time frame, may result in a differential reliance on the two systems between early childhood and adulthood.

III The declarative/procedural model: First and second language

In the previous section we summarized the neurocognitive fundamentals of the two memory systems. Here we discuss how these fundamentals are expected to apply to language. In particular, the DP model posits that the declarative and procedural memory systems should play roles in language that are largely analogous to the roles they play in other domains. Thus, our independent knowledge of the two memory systems, as laid out above and in more detail elsewhere (e.g. see Ullman, 2015, 2016), leads to quite specific hypotheses for language. For more on these hypotheses, see Ullman (2004, 2015, 2016). More generally, for a detailed discussion of the growing role of neurolinguistic research in shaping theories of SLA, see Roberts et al. (2016).

Here we briefly summarize the basic non-neurobiological hypotheses, including examining similarities and differences between first and second language. (For empirical evidence testing the DP model, see, especially for L2, Babcock et al., 2012; Bowden et al., 2013; Faretta-Stutenberg and Morgan-Short, 2018; Hamrick et al., in preparation; Morgan-Short et al., 2010; Morgan-Short, Finger, et al., 2012; Morgan-Short, Steinhauer, et al., 2012; Tagarelli et al., in preparation; Ullman, 2015, 2016.)

In certain respects the claims of the DP model are similar in first and second language. In both L1 and L2, declarative memory should underlie the learning, storage, and use of all idiosyncratic knowledge in language, since all such knowledge may have to be learned in this system. Thus, declarative memory should be crucial for all learned idiosyncratic (non-derivable) linguistic knowledge, at the word or multi-word level. The learning of simple content words (e.g. *cat, devour*), including their phonological forms, meanings, (sub)categorization knowledge (e.g. *devour* requires a complement), and mappings between them (e.g. sound–meaning mappings), should therefore depend on this system. Similarly, knowledge about irregular morphological forms, both inflectional and derivational (e.g. *dig–dug, solemn–solemnity*), should be stored in declarative memory, as should idiosyncratic knowledge at the multi-word level, such as of the meanings of idioms.

Moreover, in both L1 and L2, aspects of the rule-governed grammar should generally be learned first in declarative memory, since declarative memory learns quickly, and, due to its flexibility, this system should be able to learn non-idiosyncratic (grammatical) as well as idiosyncratic aspects of language. However, in parallel, procedural memory should gradually also learn grammatical knowledge, since this system is well suited for learning implicit knowledge about rules, sequences, and categories. Grammatical knowledge is likely to be learned and stored differently in declarative and procedural memory; e.g. as chunks or explicit rules in the former, and as implicit rules that apply rapidly and automatically in the latter. For example, initially a learner may memorize complex forms such as *walked* or *the cat* as chunks in declarative memory, while, in parallel, he or she should gradually learn the underlying compositional rules. After sufficient experience with the language, procedural memory-based grammatical processing should tend to take precedence over analogous declarative knowledge, resulting in increasing automatization of the grammar.

However, L2 learning is also expected to differ in important ways from L1 acquisition. Perhaps most importantly, grammar should tend to depend more on declarative memory and less on procedural memory in L2 than L1, for several reasons.

First, learners will always have had less L2 than L1 language exposure at a given chronological age (assuming continued exposure to both), simply because they began learning the L2 later. The later the L2 age of acquisition, the more pronounced this difference. Since procedural memory learns only gradually, at any given age a learner's L2 grammar should therefore be less proceduralized than their L1 grammar (i.e. it should be learned to a lesser extent in procedural memory), and should thus depend relatively more on declarative memory. Just for this reason alone, L2 grammar should tend to rely more on declarative memory than L1 grammar in a given learner.

Second, as we have seen above, learning and consolidation in procedural memory may peak early in life and then decline, while declarative memory shows the opposite pattern. Therefore, L1 learners (as well as early L2 learners) should tend to rely particularly on procedural memory for learning grammar (especially after a reasonable amount of language exposure), whereas later (L2) learners should show more reliance on declarative memory, and indeed may never proceduralize their grammar to the same extent as L1 learners. We emphasize, however, that substantial proceduralization of the grammar (that is, learning in procedural memory) may be expected even in L2, since procedural memory seems to be only attenuated, rather than defunct, in later learners, including adults. The extent to which L2 learners proceduralize their grammar remains an open question, and likely depends on various factors, including individual differences. For example, evidence suggests that the better an L2 learner's procedural memory, the better their grammar (Hamrick, 2015; Hamrick et al., in preparation; Morgan-Short et al., 2014), suggesting that L2 learners with better procedural memory (not surprisingly) proceduralize their grammar to a greater extent, leading to better grammatical abilities. Note that proficiency is at least partly independent of proceduralization, since high levels of proficiency may be reached for at least some aspects of grammar even while relying on declarative memory (Prado and Ullman, 2009; Ullman, 2015).

Third, the type of language experience (the learning context) may influence the learner's relative dependence on the two memory systems for grammar. Given that explicit knowledge is learned only in declarative memory, explicit (classroom-like) instruction of the grammar may encourage learning in this system, perhaps at the expense of learning in procedural memory. Similarly, increasing attention and awareness of linguistic forms, which can lead to increased explicit knowledge (DeKeyser, 2015; Rosa and Leow, 2004), should also facilitate learning in declarative memory. Conversely, the lack of explicit instruction, as examined in implicit SLA learning paradigms, and as often occurs in immersion contexts, may result in a greater dependence on procedural memory. These predictions should hold for both L1 and L2 learners, though given the prevalence of explicit instruction in L2 learning, second language learners may be expected to depend particularly on declarative memory.

Finally, we emphasize that it is not the case that changes in the relative reliance on the two memory systems in language learning are due to any 'transformation' of knowledge from one to the other system. Rather, as described above, based on independent research on the two systems, it appears that redundant knowledge is learned largely in parallel across them (e.g. as chunks such as ‘walked’ in declarative memory and as implicit rules such as ‘add *-ed*’ in procedural memory). However, since declarative memory typically learns more rapidly than procedural memory, the former will generally be relied on more initially. As exposure to the input continues however, learning in procedural memory and corresponding automatization will progress, until, at some point, the procedural knowledge may be strong enough to take precedence over declarative knowledge, and thus be relied on instead. It is not clear how this view corresponds to SLA models of the interface between explicit and implicit knowledge. It seems to differ from both the ‘non-interface’ position, which argues that explicit knowledge can never become implicit knowledge (Krashen, 1982), and the ‘strong interface’ position, which argues that explicit knowledge transforms into implicit knowledge through proceduralization (DeKeyser, 2015). The DP model’s claims might be most consistent with the ‘weak interface’ position, which (in one version) argues that explicit and implicit knowledge rely on distinct systems that interact in language learning and use (Ellis, 2005). However, it is important to keep in mind that the explicit/implicit dichotomy is not isomorphic to the declarative/procedural distinction. For example, both memory systems underlie implicit knowledge, which is moreover subserved by other memory systems as well (Ullman, 2015). Thus, it is difficult to directly compare the SLA and DP model positions.

IV The enhancement of learning and memory

Our independent understanding of declarative and procedural memory leads to hypotheses regarding not only how language is learned, stored, and used, but also how these processes can be improved. A long history of memory research has revealed a range of interventions (i.e. techniques) that may improve functioning in one or both systems. According to the DP model, one should also be able to employ such interventions to improve the learning, storage, or use of language.

Some such interventions are relatively invasive, and directly target the underlying neurobiological systems. For example, various pharmacological agents, such as methylphenidate, memantine, and acetylcholinesterase inhibitors, are known to enhance declarative memory (Dommett et al., 2008; Repantis et al., 2010), while others, such as levodopa (a precursor to the neurotransmitter dopamine), may enhance procedural memory (de Vries et al., 2010). However, as these methods are somewhat invasive (defined in a broad sense), they tend not to be used for most non-clinical applications. Thus, here we focus on non-invasive methods, which may be more readily applicable to second language learning and pedagogy.

Non-invasive interventions may be classified into at least two broad types: first, those that improve the learning and memory of the specific items or skills to which they are applied in a given learner (here we will refer to these as ‘item-level’ approaches); and, second, those that enhance learning and memory more broadly in an individual (we will refer to these as ‘learner-level’ approaches).

Item-level techniques that have been shown to improve learning or retention include the following:

- spaced repetition (also known as distributed practice, or the spacing effect; i.e. introducing temporal gaps between repeated presentations of the same item; Cepeda et al., 2006)
- retrieval practice (also known as the testing effect; i.e. retrieving learned information from memory instead of restudying it; Roediger and Butler, 2011)
- deep encoding (engaging in semantically rich processing as opposed to surface-level processing of information; this is also discussed in terms of levels of processing theory; Craik and Tulving, 1975)
- gesture-based learning (also known as the enactment effect; e.g. accompanying word learning with contextually appropriate gestures; Macedonia, 2014)
- mnemonic strategies such as the method of loci (also known as memory palace; i.e. mentally mapping to-be-learned material onto imageable locations; Lea, 1975)

All five of these approaches seem to benefit declarative memory (e.g. they are used on idiosyncratic material), while at least spacing may also apply to procedural memory (see below).

Learner-level interventions are generally less well understood, but include sleep (important for consolidating new declarative and/or procedural memories; e.g. Mednick et al., 2011; Rasch and Born, 2013), aerobic exercise (may augment hippocampal volumes as well as aspects of declarative memory; Erickson et al., 2011) (but see Hillman et al., 2008), diet (e.g. flavanols may improve declarative memory in older adults; Brickman et al., 2014), and mindfulness (which may improve declarative but inhibit procedural learning; Stillman et al., 2014).

As mentioned above, here we focus on spaced repetition and retrieval practice, two non-invasive item-level behavioral approaches. As we shall see, both have been well studied in general, both have been linked to declarative memory (and spaced repetition has been linked to procedural memory as well), and both have begun to be applied to language learning.

I Spaced repetition (the spacing effect)

Given a fixed amount of total study time, how should a learner optimally schedule study? Study schedules in which repetitions of the same or similar items (or tasks) occur with intervening temporal gaps (from seconds to minutes to even days, months, or years) result in better retention than schedules in which the same number of repetitions occur in close succession. This advantage is called the spacing effect. In other words, if a given item is presented with temporal space (time) between presentations, retention of the item is better than with massed presentation, that is, without spacing between items.

A substantial empirical literature has revealed a number of important characteristics of the spacing effect. First of all, longer gaps tend to result in longer retention than shorter gaps (this advantage of longer vs. shorter gaps is also referred to as the ‘lag effect’) (Cepeda et al., 2006). For example, a gap of one day should result in longer retention than a gap of one hour. However, note that at some point longer gaps seem to result in diminished retention (Cepeda et al., 2008). Second, and quite usefully, the length of the optimal gap necessary to maximize the retention of knowledge for a given period is proportionally smaller for longer than shorter retention periods (Cepeda et al., 2008). For example, some evidence suggests that given two study sessions, the optimal gap for maximizing retention for a week requires the sessions to be spaced apart by about 20 to 40% of this period (about 2 days), whereas the optimal gap for maximizing retention for a year requires sessions to be spaced apart by only about 5%–10% of this period (about 25 days) (Cepeda et al., 2008, 2009). Third, it has been suggested that increasing the length of inter-repetition gaps over the course of learning ('expanding gaps') can increase retention as compared to fixed gaps; however, this claim should be treated with caution, since findings have overall not clearly supported an advantage for expanding gaps (for a review, see Balota et al., 2006). Fourth, for very short retention delays, and in particular for no delay at all (i.e. when learners are tested immediately after learning, as when 'cramming' for a test), the advantages of spacing may disappear and might occasionally even reverse, suggesting that in such circumstances it might be advantageous to mass, rather than space, items (Raaijmakers, 2003). (But see Cepeda et al., 2006; also see below regarding motor skills). Fifth, this pattern suggests in turn that spacing may generally enhance retention rather than learning, since spacing typically yields larger advantages after delays than immediately after learning.

Thus, on a practical level, the evidence suggests that the selection of gap durations should take into account both (1) how quickly the information must be learned (shorter gaps should generally lead to faster acquisition, since more material is presented in a particular period of time) and (2) how long the information must be retained (longer gaps lead to longer retention, at least up to a point). It should be kept in mind, however, that although longer gaps produce longer retention, no spacing effect is possible until at least one gap has elapsed (that is, until the item has been encountered at least twice). We also emphasize that the spacing effect refers to comparisons between spaced and massed (or less spaced) presentations with the same number of repetitions in each condition; additional repetitions, for example within the temporal gaps, may be expected to further increase learning and retention (although this would also result in less spacing, complicating the issue). Indeed, this is an important advantage of an expanding gaps approach (see above), in that the learner receives more repetitions early on, and thus learns more quickly (Landauer and Bjork, 1978), even if such a study schedule might not reliably yield better retention than one with fixed gaps (see above; Balota et al., 2006).

Explanations of the spacing effect continue to evolve, even after decades of accumulated research. Here we briefly review three broad classes of explanations. First, 'deficient processing' theories of spacing (e.g. Hintzman, 1974, 1976) posit that the greater the amount of processing an item undergoes at training, the more likely it is to be recalled at test. Since subsequent occurrences of an item in spaced repetition should receive more processing than in massed repetition (e.g. they should be less familiar, and thus require more attention), items in spaced repetition should receive overall more processing, and therefore should be retained longer. Second, 'encoding variability' theories of spacing (Glenberg, 1979; Madigan, 1969; Melton, 1970) contend that the greater the overlap between the contextual information present during encoding (learning) and the contextual information present during test, the greater the probability of success at test, since any contextual features present during learning should help with retrieval at test. Since context is assumed to drift with time, in massed repetition there should be high overlap between the encoding contexts (since the repetitions are likely to take place in the same contexts). In contrast, when items are spaced, contextual information has a greater opportunity to drift between repetitions, so items should be associated with more contextual features. Context is also assumed to continue drifting during the retention interval, so the context at test after this delay is likely to be different from that during study. Therefore the larger number of contextual features provided by spaced as compared to massed study should provide more retrieval cues for the learner. Encoding variability theories can also help explain why massed study tends to yield better outcomes when followed by no (or a short) delay before test, since in this case the study and test contexts should be highly overlapping. Third, consolidation theory (Wickelgren, 1972) claims that the consolidation of an item's first presentation facilitates the consolidation of the item at its next presentation. The longer the gap, the more the first presentation can be consolidated, and thus the more successful the consolidation of the next item. In sum, although the mechanisms underlying the spacing effect remain to be fully elucidated, as we shall see, the associated pattern of results is quite compelling, whatever the explanation(s).

A large literature has examined spacing effects in a wide range of contexts, and overall spacing shows medium to large effect sizes, as revealed by meta-analyses (Donovan and Radosevich, 1999; Lee and Genovese, 1988). Spacing has been found to be effective for multiple tasks and domains, including the following: verbal learning tasks of many sorts, such as word list learning, paired associates learning, and paragraph recall (Cepeda et al., 2006); remembering faces (Xue et al., 2011); learning various types of information in school (including in classroom contexts) such as in physics (Grote, 1995), biology (Vlach and Sandhofer, 2012), mathematics (Rea and Modigliani, 1985), and various medical school topics (Kerfoot and Brotschi, 2009); acquiring skills as diverse as spelling (Rea and Modigliani, 1985), dance (Batson and Schwartz, 2007), music (Simmons, 2012), and surgery (Mackay et al., 2002); remembering advertising content (Janiszewski et al., 2003); learning personality traits (Bird, 1987); acquiring visuospatial skills (Metalis, 1985); learning motor skills (Lee and Genovese, 1988) such as rotary pursuit (Bourne and Archer, 1956); sequence learning in the serial reaction time task (Kwon et al., 2015); and generalizing from learned examples (e.g. learning abstract science concepts from a few examples; Vlach and Sandhofer, 2012). Interestingly, a category induction task (identifying artists by exemplars of their work) showed a spacing effect despite higher participant confidence after massed presentation, which might have been expected to highlight commonalities between works, thus making generalization easier (Kornell and Bjork, 2008). Nevertheless, there may be limitations to spacing effects with respect to certain material. For example, some evidence suggests that the effect of spacing diminishes and may even disappear with very complex material (Donovan and Radosevich, 1999).

In general, although spacing effect studies are generally not linked specifically to either declarative or procedural memory, many such studies clearly involve declarative memory, in particular those that examine the learning of idiosyncratic information, such as words, academic facts, or faces. The theoretical links to attention also implicate this system. There has been less work on spacing effects in procedural memory. Nevertheless, many early studies reported spacing effects in implicit skill learning, including of motor skills (Lee and Genovese, 1988). Moreover, spacing effects have been observed in tasks directly linked to procedural memory, such as rotary pursuit (Bourne and Archer, 1956) and the serial reaction time task (Kwon et al., 2015). Thus, spacing advantages also seem to hold for learning in procedural memory (Donovan and Radosevich, 1999; Lee and Genovese, 1988). Interestingly, whereas spacing (e.g. compared to massed presentation) has generally been found to lead to greater benefits following a retention delay than immediately after training (see above), some evidence suggests that motor skills, which might be learned largely in procedural memory, show spacing advantages immediately after training that may even be larger than those after a retention delay; although, note that even after such a delay spacing still shows substantial advantages as compared to massed presentation (Bourne and Archer, 1956; Lee and Genovese, 1988).

2 Retrieval practice (the testing effect)

Whereas the spacing effect acts on study schedule, retrieval practice is concerned with study activity. The retrieval practice effect (the testing effect) refers to the phenomenon that studying by testing, in the general sense of retrieving information from memory, leads to better recall or recognition on delayed assessments as compared to simply 'restudying' (e.g. rereading) the same material. This phenomenon may have important practical implications, since many students study by rereading their notes or textbooks, while fewer study by testing themselves on this information (Karpicke, 2009). Indeed, after retrieval practice students have been found to express lower confidence in their knowledge of the material than after an equivalent amount of time rereading (Karpicke, 2012), reflecting the perception that testing oneself is less effective than restudying.

Research has revealed a number of important attributes of retrieval practice, with potentially useful pedagogical implications. First, as with spacing, the benefits of retrieval practice often emerge only after a delay, before which restudy is either as useful or more useful than retrieval practice (Roediger and Karpicke, 2006; but see Smith et al., 2013). Second, and relatedly, some evidence suggests that the longer the retention delay, the greater the advantage of retrieval practice over restudy (but see Carpenter et al., 2008; Rowland, 2014). The advantage of retrieval practice over restudy should thus be greater if one's knowledge is tested a year later as compared to a month later (though of course for both retrieval practice and restudy more forgetting will occur after one year than after one month). This suggests that retrieval practice (like spacing) is particularly beneficial if a learner's goal is long-term retention of material. Third, factors that increase the difficulty of retrieval during training often (but not always) further improve retention. For example, training with free recall (retrieval with no cue) generally results in greater retention than training with cued recall, which in turn leads to better retention than training with recognition tasks (Carpenter and DeLosh, 2006). Fourth, the presence or absence of feedback also seems to modulate the testing effect. In particular, providing the correct answer following a response attempt increases the magnitude of the advantage of retrieval over restudy (Roediger and Butler, 2011). Note that feedback can benefit both incorrectly and correctly recalled items: in addition to allowing learners to correct their knowledge of incorrectly recalled items, feedback also seems to improve knowledge (and thus retention) of items that were recalled correctly, but with low confidence (Butler et al., 2008). Interestingly, delayed correct-answer feedback (e.g. a day after retrieval) seems to offer greater benefits over immediate feedback (Butler et al., 2007; Pashler et al., 2005), perhaps because the delay between testing and feedback acts as a study gap (consistent with the spacing effect) (Butler et al., 2007; Metcalfe et al., 2009).

As with the spacing effect, a full mechanistic account of the testing effect remains elusive, although a number of explanatory accounts have been proposed. Here we focus on a few important ones. First of all, a number of explanations, such as the 'new theory of disuse' (Bjork and Bjork, 1992) and the 'bifurcation model' (Kornell, Bjork, and Garcia, 2011), are rooted in the framework of 'desirable difficulties' (Bjork, 1994), which posits that, in general, the greater the effort invested in encoding, the higher the likelihood of retrieval at test. Since retrieval is more effortful than restudy, retrieval practice should be more likely to promote successful retrieval at test. Note the similarity of these accounts to 'deficient processing' theories of the spacing effect, in that both are premised on the idea that greater effort leads to greater retention. Second, the 'episodic context' account (Karpicke et al., 2014), like 'encoding variability' theories of the spacing effect, is premised on the assumption that a learner's context drifts with time. The account claims that since retrieval of an item involves a search that relies on the context with which the item has been associated, retrieval will tend to activate an item's previous encoding(s), which are then combined with the present context. Thus retrieval creates an enriched context based on the combination of contexts in which the item has been retrieved. This in turn leads to multiple retrieval routes, raising the probability of recall during final test. In contrast, since restudy does not require search, previous context(s) are less likely to be accessed, so the overall context is likely to be relatively impoverished, in turn leading to a lower probability of recall at test. Third, according to the 'elaborative retrieval' hypothesis (Carpenter, 2009; Carpenter and DeLosh, 2006), performance will be better on a final retention test when more elaborative memory traces are formed during practice. On this view, attempting to retrieve an item from memory tends to activate semantically related items due to the search process; it is posited that these related items can serve as cues during subsequent retrieval. Restudy elicits less such activation, because the learner is provided the target item, obviating the need for search. Overall, it remains to be seen which of these (or other) accounts of the testing effect will have the greatest explanatory power.

The testing effect seems to be reasonably robust. One meta-analysis found an overall medium effect size for the advantage of retrieval practice over restudy, with small to large effect sizes depending on various moderator variables (Rowland, 2014). Additionally, like the spacing effect, the testing effect has been observed for many types of information. Advantages after a delay have been found for retrieval practice as compared to restudy on the learning of prose passages (Roediger and Karpicke, 2006), verbal paired-associates (Carrier and Pashler, 1992), historical facts (Carpenter et al., 2009), word lists (Carpenter and DeLosh, 2006), proper names (Morris et al., 2005), face–name pairs (Weinstein et al., 2011), and spatial locations (Pashler et al., 2007), among other tasks (Rowland, 2014). Importantly, while most work on the testing effect has taken place in the laboratory, the effect has also been shown in classroom settings (Leeming, 2002; Lyle and Crawford, 2011; McDaniel et al., 2007; Orr and Foster, 2013).

Research on retrieval practice has focused on tasks that appear to involve learning in declarative memory, as evidenced by the idiosyncratic nature of the learned information. The theoretical links to episodic contexts also implicate this system. We are not aware of any studies examining the testing effect on procedural memory. Indeed, it may be difficult to apply retrieval practice to procedural memory, since explicit awareness seems to be inherent in the type of retrieval generally examined in this phenomenon, and only declarative memory underlies explicit knowledge. Moreover, some evidence suggests that learning in declarative memory might interfere with aspects of procedural learning (Poldrack and Packard, 2003), suggesting that retrieval practice might plausibly have a similarly detrimental effect. Alternatively, since practice, which is critical for procedural learning, might perhaps be considered to involve retrieval (i.e. one presumably retrieves skill knowledge when practicing), one might argue that retrieval practice is necessary for all procedural learning. It is unclear whether this perspective might offer any potential for the enhancement of learning in procedural memory.

3 Spaced retrieval practice (spaced testing)

Although most studies consider the effect of either spacing or retrieval practice in isolation, we are aware of one study that specifically examines whether combining these two interventions leads to better recall than either intervention on its own. (Note that many studies of the testing effect include repeated training tests, and thus tend to include spacing between them; however, these do not specifically examine the spacing effect in that they do not compare more vs. less or no spacing.) This study, which investigated the learning of face–name pairs, found that spaced retrieval practice (both interventions combined) yielded better memory for the material after a 5 minute delay than either spaced study or massed retrieval practice (which yielded similar memory outcomes), which in turn resulted in better outcomes than massed study (i.e. with neither intervention) (Carpenter and DeLosh, 2005). Another study, which tested longer retention (up to 8 days) of paired associates, compared spaced retrieval practice to only spaced study, and reported retention advantages for the former (Cull, 2000). Additionally, evidence suggests that spaced retrieval practice yields better retention than massed retrieval practice (Karpicke and Roediger, 2007; Landauer and Bjork, 1978; Rea and Modigliani, 1985). Based on these results, it seems likely that spaced retrieval practice offers a promising method of improving retention even beyond either intervention on its own, at least in declarative memory (since these studies used tasks that appear to depend on this system), although clearly more research on this topic is needed.

V Spaced repetition and retrieval practice in language learning: Predictions and evidence

As we have seen, the retention advantages of spaced repetition and retrieval practice apply broadly to declarative memory, and, at least in the case of spacing, likely to procedural memory as well. According to the same logic by which the DP model makes predictions about language in general, it follows that these interventions should similarly improve language learning, in particular language retention. Moreover, as we shall see, the exact situations in which language retention should be improved should depend in part on the neurocognitive reliance of language on the memory systems; that is, which aspects of language depend in which circumstances on which memory systems.

1 Spaced repetition in language learning

Given that spacing seems to improve retention in declarative and probably procedural memory, we predict that it does likewise for language. Moreover, since greater spacing yields longer retention benefits, the same outcome should be found for language learning. Indeed, as we shall see, studies have found spacing benefits in both L1 and L2, for both vocabulary and grammar, including greater retention benefits from more spacing. Note that since spacing may improve retention in both declarative and procedural memory, this technique may be expected to apply successfully to aspects of language that depend on both memory systems; that is, lexical and grammatical knowledge, at earlier and later stages of learning, in explicit and implicit learning contexts, in both L1 and L2.

Spacing effects in L1 learners have been probed in only a small number of studies. All studies that we are aware of that have examined spaced repetition in vocabulary learning in L1 have found advantages, not only in the laboratory (Childers and Tomasello, 2002; Dempster, 1987; Kornell, 2009), but also in the classroom (Goossens et al., 2012; Sobel et al., 2011). We are aware of only one study that has examined spacing in L1 grammar acquisition. In this study young children learned a previously-unknown grammatical construct (object-cleft) from exemplars, with either spaced or massed presentation (Ambridge et al., 2006). They were then tested on the production of this construct at the end of the fifth day of training. The children who had been presented with spaced exemplars outperformed those presented with massed exemplars. Since the children were not given explicit instruction on the construction, which was presented according to typical implicit learning paradigms, it is possible that this task may have tapped procedural memory, though it could also have been learned in declarative memory.

A somewhat larger literature has examined spaced repetition in L2 learning, in particular for vocabulary (Bahrick, 1979; Bahrick et al., 1993; Bahrick and Phelps, 1987; Bloom and Shuell, 1981; Kupper-Tetzel et al., 2014). One especially striking pair of early studies demonstrated a spacing effect in L2 vocabulary (in which native English speakers learned Spanish words) in undergraduate students (Bahrick, 1979), and then conducted an eight-year follow-up study (Bahrick and Phelps, 1987). Together, these laboratory studies found that a study gap of 30 days in the initial training yielded, eight years later, a probability of recall 2 times greater than a study gap of one day, and 2.5 times greater than no study gap (massed study). If the goal of second language learning is long-term retention, this result argues strongly in favor of spaced learning strategies. Moreover, as expected, these studies suggest that longer gaps yield better long-term retention than shorter gaps. Classroom studies also suggest L2 word learning advantages from spacing. Spaced repetition of L2 vocabulary terms has been found to improve recall on tests delayed by both 7 and 35 days in middle-school students (Kupper-Tetzel et al., 2014), on tests delayed by one month in middle-school students using spaced-repetition software (Lindsey et al., 2014), on tests delayed by 4 days in high-school students (Bloom and Shuell, 1981), and on tests delayed by 7 days in college students (Nakata, 2015). Overall, the evidence thus suggests that spacing effects do indeed extend to L2 vocabulary learning, even benefiting retention for periods of years. Note that a number of studies have examined English native speakers learning foreign-language–English word pairs, to test either the spacing and/or testing effect (Carpenter et al., 2008; Carrier and Pashler, 1992; Kang et al., 2014; Karpicke and Bauernschmidt, 2011; Karpicke and Roediger, 2008; Pavlik et al., 2005; Pyc and Rawson, 2007); although, as expected, these studies do indeed find both effects, they are not discussed here because the learners are tested on the English words, and thus the studies do not, strictly speaking, examine L2 learning, even though they are often discussed as L2 word learning studies.

Studies of the spacing effect in L2 grammar are less common, though the limited research carried out to date suggests spacing advantages in this domain as well. The spacing of explicit instruction on tense and aspect has been found to improve retention of this knowledge (Bird, 2010). Similarly, spaced explicit instruction of adverb use seems to be more resistant to forgetting than massed explicit instruction (Miles, 2014). Another study, which examined the effects of spaced explicit instruction (with various forms of practice) on Japanese verbal inflectional morphology, did not find retention benefits of spacing (Suzuki and DeKeyser, 2015); the authors attributed this null result to the complexity of the task, since more complex tasks have been found to show less of a spacing advantage (Donovan and Radosevich, 1999). To our knowledge, two studies have examined spacing advantages in L2 grammar using somewhat implicit learning tasks. One study found spacing advantages (42 days after training, with no spacing advantage immediately after training) in college students who were trained on grammatically complex sentences by simply viewing them and answering comprehension questions (Rogers, 2015). In another study (not actually designed to examine spacing effects), which found a small spacing advantage, ditransitive verbs were first defined, and then participants viewed videos illustrating these verbs, with accompanying narration using appropriate ditransitive constructions (Year and Gordon, 2009). Given the implicit nature of the learning contexts, these two studies may have tapped procedural memory for grammar learning, though a reliance on declarative memory is by no means excluded. Thus, although the link between spacing and declarative memory advantages seems quite well established for vocabulary, with some evidence for grammar as well from explicit learning contexts, more research is needed to shed light on potential spacing advantages for the procedural learning of grammar.

Related to the spacing effect, a substantial literature in SLA has examined the effects of intensive, relatively massed, L2 instruction (intensive courses) versus more distributed (spaced) learning (regular L2 courses). Although, apparently contrary to the spacing effect, these studies have generally found advantages for intensive vs. regular L2 courses (Serrano, 2012), several confounds and weaknesses of such studies have been pointed out (Rohrer, 2015; Serrano, 2012). First, the selection criteria for placement in intensive language classes are often more stringent than for regular classes, potentially resulting in more talented or advanced learners in the former. Second, intensive language classes often include more instructional or other language contact time than equivalent regular language classes. Third, in most cases, such studies have tested learners only immediately following training, and not after a delayed retention interval, at which point spacing effects are generally strongest. Thus, the jury is still out as to whether or not regular classes may show the expected spacing benefits as compared to intensive classes.

2 Retrieval practice in language learning

Given that retrieval practice (i.e. the testing effect) clearly applies to declarative memory, we expect that this technique should show retention benefits for all aspects of language learning that depend on this system, including vocabulary learning, early stages of grammar learning, and grammar learning in contexts that foster a reliance on declarative memory, such as explicit instruction or increased attention to the stimuli or underlying rules (see Sections II and III; Andringa and Rebuschat, 2015; Gass and Mackey, 2012; Rebuschat, 2015; VanPatten and Williams, 2015). Note that although retrieval practice may not benefit learning in procedural memory, if it does (Section IV.2) we would expect that it should improve retention of grammar learning at later acquisition stages and in implicit learning contexts. Finally, as with the broader literature on retrieval practice, any benefits from this technique should be greater, as compared to restudy, for longer retention periods.

As we shall see, the testing effect has been much less well studied than the spacing effect in language learning. Nevertheless, we are aware of a small number of studies, which indeed suggest word learning advantages from retrieval practice in both L1 and L2. To our knowledge the testing effect has not yet been investigated in grammar learning, in either L1 or L2. Moreover, increasing advantages of retrieval practice with longer retention intervals have only been examined in one language study, which found no differences in the retrieval practice advantage between shorter and longer retention periods (Barcroft, 2007; see below). Thus substantial gaps remain in the investigation of the effects of retrieval practice on language learning.

We are aware of one study examining the testing effect in L1 vocabulary learning. In this laboratory study, primary-school students showed a retrieval practice advantage, as compared to restudy, for recall (but not recognition) both when the words were embedded in the context of a story and when they were presented alone (Goossens et al., 2014). Additionally, and relevant to word learning, retrieval practice benefits for spelling have been found in beginning spellers (Jones et al., 2016), although for adult spellers the results have been mixed (Pan et al., 2015). We are not aware of any studies examining the testing effect in L1 grammar.

The effects of retrieval practice in L2 learning have also been examined by few studies (Barcroft, 2007; Kang et al., 2013; Metsamuuronen and Mattsson, 2013), although these have revealed retrieval practice advantages for both word learning and general language measures. In one study, performed in the laboratory, native English speakers learning Spanish were trained on picture–word pairs (with novel Spanish words) under either retrieval practice or restudy conditions (Barcroft, 2007). Retrieval practice advantages were found on both two-day and one-week delayed tests. There was no difference in the retrieval practice advantage between these two delays. Another laboratory study found retrieval practice advantages (as compared to repeating after a native speaker) for both comprehension and production of Hebrew words in English native speakers (Kang et al., 2013). In another study, carried out in the classroom, adult learners of Hebrew either studied or were tested on Hebrew material ranging from grapheme-recognition to vocabulary and grammar production, twice a week for several weeks (Metsamuuronen and Mattsson, 2013). At the end of training, students in the retrieval practice condition had improved significantly more than students in the study condition, compared to a pre-test. Only general language measure outcomes were reported (i.e. not specific measures of vocabulary or grammar).

Overall, the limited evidence to date suggests retrieval practice benefits for word learning in both L1 and L2. As mentioned above, we are aware of no studies investigating retrieval practice effects specifically in grammar learning, in either L1 or L2. Thus research on retrieval practice effects in grammar seem warranted. We predict that to the extent that grammatical knowledge is learned in declarative memory (as is predicted by the DP model for early stages of grammar learning, especially under explicit learning conditions; see above and Ullman, 2015, 2016), retrieval practice should improve retention of grammar. However, since explicit input may inhibit procedural learning (Ullman, 2015, 2016), it is also possible that retrieval practice leading to improved grammar learning in declarative memory might simultaneously inhibit grammar learning in procedural memory. Future studies should elucidate these issues.

3 Spaced retrieval practice in language learning

As discussed above, some research suggests that the combination of spacing and retrieval practice may be particularly effective at improving retention, at least for information learned in declarative memory. Therefore spaced retrieval practice may offer benefits to those aspects of language that depend on declarative memory, such as word learning, early stages of grammar learning, and grammar learning in explicit contexts. Although we are aware of no studies of spaced retrieval practice of grammar learning (leaving an important gap for further research), one recent study compared spaced retrieval practice to massed study in L2 vocabulary learning (Ozemir et al., in preparation).

This study examined Turkish university students learning English, who were randomly assigned to either of two conditions. In one, participants were presented with the words massed in two clusters, with three presentations on the first day of training and three on the last day of training, 8 days later. This was designed to mimic typical teaching and learning contexts, where students study items first when learning them, and then again later before they are tested on them. The other condition was designed to combine both spacing and retrieval practice (the design did not independently test the two effects). The participants in this second condition actively retrieved the words (i.e. English words from their Turkish equivalents), rather than passively restudying them; moreover, the training sessions were spaced out over the entire training period. Participants from both groups were tested on vocabulary prior to training (pre-test), and then again both one day and 11 days after the end of training. The learners trained in the spaced retrieval condition improved significantly more than those in the massed study condition, and moreover performed better at retention intervals both one and 11 days after training, with no difference between these retention periods in the spaced retrieval advantage. The study suggests that the combination of spacing and retrieval may constitute a pedagogically useful approach. Further research, in particular examining spaced retrieval compared to each intervention on its own, seems desirable.

VI Summary and discussion

The declarative/procedural (DP) model makes predictions not only for the neurocognition of language, but also for how language learning, storage, and use can be enhanced. These predictions follow from independent research suggesting that particular techniques (interventions) can enhance learning and memory in the declarative and/or procedural memory systems. According to the DP model, these same techniques are likely to apply in similar ways to language learning.

A variety of learning and memory enhancement approaches have been investigated. Non-invasive interventions, which are of particular interest for L2 learning and pedagogy, can be classified into at least two types: item-level approaches, which can improve the learning and memory of the particular items or skills to which they are applied in a given individual (e.g. spaced repetition, retrieval practice, deep encoding, the enactment effect, and the method of loci), and learner-level approaches, which may improve learning and memory in the individual more broadly (e.g. sleep, exercise, diet, and mindfulness).

We have discussed in some depth two approaches – spaced repetition (the spacing effect) and retrieval practice (the testing effect) – since both of these item-level techniques are well studied and quite effective, and they can be combined. Moreover, both rely on declarative memory and, in the case of spacing, procedural memory as well. Finally, both are particularly effective for the *retention* of language, which is generally the goal of language learning. After providing an overview of these techniques from the memory enhancement literature, and their links to declarative and procedural memory, we laid out the DP model's specific predictions for both techniques for the enhancement of language learning, and summarized the evidence to date, with a focus on second language acquisition.

Overall, the existing evidence suggests that, consistent with the DP model's predictions, both spacing and retrieval practice can enhance language learning, in particular retention, for both L1 and L2. The effects of spacing on language have been fairly well studied. For the most part, this research has focused on L2, especially vocabulary learning. The findings suggest that spacing yields clear retention advantages for word learning, even years later. There has been less research on the effects of spacing on grammar learning, but even here retention advantages have been observed in L2 in both explicit and implicit training paradigms. Less work has studied the effects of retrieval practice on language, though vocabulary retention seems to benefit from this approach as well. We are not aware of any studies examining the effects of retrieval practice on grammar learning. Finally, one recent study of L2 vocabulary learning examined the combination of spaced repetition and retrieval practice, and reported a substantial retention benefit compared to neither intervention.

Thus, the literature investigating the effects of spacing and retrieval practice on language learning, though still small, is quite promising. The findings provide at least preliminary support for the DP model's predictions laid out above regarding the enhancement of language learning (see Sections V.1, V.2, and V.3). However, many of these predictions have not been examined thoroughly, and some not at all, leaving important gaps for future research. For example, we are not aware of any work investigating the effects of either technique in explicit vs. implicit language learning contexts, or comparing different stages of grammar learning. Future research further examining these predictions seems warranted.

Importantly, based on the broader literature investigating the two techniques, the DP model also makes a number of pedagogical predictions that may be directly relevant to SLA learners and educators.

First of all, the model makes various pedagogical predictions about spaced repetition. Given the effectiveness of spacing, language educators should space out coverage of topics, rather than introducing and completing each one (e.g. the subjunctive) before moving on to the next. This principle should apply not only over the course of a semester or year, but even across longer periods of time. This may have important consequences for curriculum design. Likewise, language learners on their own should space their study out over weeks, months, or even years, continually coming back to the same material. Given that spacing appears to be effective for learning in both declarative and procedural memory, the technique may be applied broadly, without worrying whether lexical or grammatical knowledge is being learned, in earlier or later stages, or in implicit or explicit contexts. Thus, spaced repetition should be relatively easy to employ and broadly effective. We emphasize, however, that the spacing effect is typically studied in comparison to less or no spacing with the same number of repetitions; as discussed above, additional repetitions, for example within the spacing gaps, may be beneficial, since in general more repetition leads to better learning and retention. Finally, since spacing seems to be generally most effective at longer retention intervals, it should be employed by learners and educators with retention benefits in mind, especially longer-term retention. As mentioned above, its utility in SLA is underscored by the fact that longer-term retention is usually the goal of language learning.

The DP model also makes pedagogical predictions about the testing effect. For example, retention of second language knowledge should benefit strongly from in-class quizzes. Note that since evidence suggests that combining retrieval practice with spacing can further enhance learning, combining both techniques in language instruction may be particularly beneficial; for example, students could be tested on the same vocabulary items in two or more quizzes spaced out in time. Additionally, students should be encouraged to test themselves rather than rereading or restudying. Small study groups to facilitate and motivate testing each other may thus be quite beneficial (Springer et al., 1999). Given that retrieval practice may apply only to declarative memory, the technique should be targeted to learning aspects of language that depend on this system, such as lexical knowledge, grammar at early stages of learning, or grammar learned in explicit contexts. Finally, as with spacing, retrieval practice may more effective at longer retention intervals, and thus should be particularly useful for longer-term language retention.

It should be kept in mind that there is still relatively little research examining the effects of spacing and retrieval practice on language learning and retention. Much more work is needed, for grammar as well as vocabulary learning, and perhaps for other aspects of language as well, such as pragmatics or prosody (which are increasingly studied in SLA; e.g., Nickels and Steinhauer, 2018). More research is needed in naturalistic settings of second language learning to examine the real world outcomes of these techniques. Since the functionality of declarative and procedural memory seems to change over the course of childhood (and adulthood), spacing and retrieval practice might be differentially effective for language learning at different ages. The utility of feedback in retrieval practice (Section IV.2) suggests the importance of investigating this phenomenon, which could help elucidate the role of feedback in second language acquisition (Gass and Mackey, 2012; Li, 2010; Mackey, 2012; VanPatten and Williams, 2015). Conversely, the extensive research on feedback in SLA could inform the role of feedback in retrieval practice. More generally, research on memory enhancement techniques in SLA should elucidate both SLA and the techniques more broadly, as well as vice versa. For example, research shedding light on the dependence of the techniques on declarative and procedural memory is needed not only to further understand the techniques themselves, but also to clarify their predicted roles in language learning. Further research should also examine how the combination of spacing and retrieval practice may benefit language learning, in particular to probe whether and how such combined approaches may be more effective than either approach on its own. More generally, much more work is needed to examine other memory enhancement interventions, perhaps especially learner-level techniques, which apply broadly within an individual, and thus do not require training on each specific item or skill. Finally, note that memory enhancement interventions should in principle be useful not only for improving second language learning and retention, but also for language recovery and rehabilitation in both neurodevelopmental and later-onset disorders, such as specific language impairment, dyslexia, autism, and aphasia (Ullman and Pullman, 2015).

In conclusion, the DP model makes clear predictions for improving learning and retention in both first and second language acquisition, based on independent findings from the memory enhancement literature. Although the research examining such predictions in both L1 and L2 learning is still somewhat limited, the evidence to date suggests that at least certain techniques, that is, spacing and retrieval practice, can indeed improve language acquisition, in particular language retention, especially for vocabulary learning, but possibly for grammar as well. These retention benefits are especially promising given the importance of retention for language learners. Importantly, both spaced repetition and retrieval practice have a number of practical pedagogical implications. Overall, we believe that these and other memory enhancement approaches should begin to be applied in pedagogical settings, though with caution, keeping in mind that more research on this topic is needed (as always, given that we are cautious scientists).

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