CHAPTER 8

FORGETTING AND COGNITIVE INHIBITION

INHIBITORY PROCESSES IN EPISODIC MEMORY

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Memory is vulnerable to forgetting. Indeed, results from a vast amount of literature clearly demonstrate that, under certain circumstances, retrieval of encoded information can fail. The circumstances under which such forgetting can arise include a number of factors that over the years have been identified to impair memory performance (for an overview, see Baddeley et al., 2015). The two most prominent factors are the retention interval between study and retrieval and the interference level at retrieval. When the delay between study and retrieval is increased, retrieval is typically impaired, reflecting so-called time-dependent forgetting (Ebbinghaus, 1885). When additional information has been encoded before retrieval, be it prior to or right after study of some target information, retrieval of the target information can suffer, reflecting so-called proactive interference (prior encoding of additional information; see Underwood, 1957) and retroactive interference (subsequent encoding of additional information; see Müller & Pilzecker, 1900).

But there are further factors beyond retention interval and the encoding of additional material that can induce forgetting. For instance, forgetting can arise when there is a mismatch between the temporal contexts at study and retrieval. Temporal context refers to the current pattern of activity in an individual's mind, which can differ between study and retrieval, for instance when the physical environment or an individual's mood has changed between the two phases (Godden & Baddeley, 1975; Eich, 1989). Because memory performance benefits from a match between the contexts at study and retrieval (Tulving & Thomson, 1973), retrieval can be impaired under such circumstances, causing so-called context-dependent forgetting. Finally, even the retrieval process itself can cause forgetting. Corresponding evidence has arisen from studies on retrieval-induced forgetting, showing that the selective retrieval of a subset of studied information can impair retrieval of other, nonretrieved information (Anderson et al., 1994).

All these factors share the characteristic that forgetting occurs incidentally and is not the result of an individual's intention to forget. However, people can also forget when cued to do so. Evidence for this proposal, for instance, has arisen from studies on directed forgetting and think/no-think impairment. Research on list-method directed forgetting has shown that providing a forget cue between the study of two lists can improve later recall of the second list items, but induce forgetting of the first list items (Bjork, 1972). Research on the think/no-think procedure has shown that when instructed to not let a previously encoded item enter consciousness, later recall of the item can be impaired (Anderson & Green, 2001). Forgetting, therefore, can arise incidentally as well as intentionally.

Over the years, a number of cognitive mechanisms have been suggested to mediate these forms of episodic forgetting, the two most prominent being retrieval competition and context change. Retrieval competition refers to the idea that memories which share a common cue – be it a temporal, semantic, or emotional cue – compete for conscious recall when this cue is provided, and as a result show reduced recall performance (McGeoch, 1932; Rundus, 1973). Retrieval competition can easily explain retroactive and proactive interference when assuming that the target information and the additionally encoded related (nontarget) information share a common retrieval cue, and thus compete for conscious recall. The proposal can also account for time-dependent forgetting, if during

the delay between study and retrieval further (related) material is encoded. But retrieval competition may also explain retrieval-induced forgetting. Indeed, if retrieval competition was strength-dependent (i.e. contents with a stronger memory representation create higher interference levels than contents with a weaker memory representation: see Rundus, 1973; Raaijmakers & Shiffrin, 1981), then selective retrieval should make the retrieved items stronger competitors for the remaining nonretrieved items, and thus induce forgetting of the nonretrieved material (Roediger & Neely, 1982; Raaijmakers & Jakab, 2012).

Context change is a second prominent mechanism. It refers to the idea that changes in the physical or mental context after study can induce a difference in contexts between study and retrieval and thus impair recall performance. Obviously, this proposal can explain typical context-dependent forgetting, such as the ocurrence of forgetting when the environment or individuals' mood has changed between study and retrieval. It can account for time-dependent forgetting when supposing that context drifts during the retention interval (e.g. Estes, 1955; Bower, 1972). It can also explain list-method directed forgetting. Here the assumption is that the presentation of a forget cue after study can induce a change in people's mental contexts, and the resulting contextual mismatch between study and retrieval impairs recall of the to-be-forgotten memory contents (Sahakyan & Kelley, 2002). More recently, context change has also been suggested to underlie retrieval-induced forgetting. Here the proposal is that the retrieval process itself creates context change (Shiffrin, 1970; Jang & Huber, 2008). Selective retrieval may therefore change people's internal contexts and thus reduce their chances to recall previously encoded nonretrieved items (Jonker et al., 2013). Retrieval competition and context change thus offer explanations for a wide range of forgetting findings.

Although retrieval competition and context change provide promising explanations of episodic forgetting, it has repeatedly been argued in the memory literature that retrieval competition and context change cannot capture the whole variety of forgetting findings and there is an additional role of inhibition in some situations. Evidence for the role of inhibition has arisen mainly in retrieval-induced forgetting, list-method directed forgetting, and think/no-think impairment. In retrieval-induced forgetting the suggestion is that during selective retrieval the nonretrieved items interfere and are inhibited to reduce the interference, which can impair later retrieval of the nonretrieved items (Anderson, 2003). In list-method directed forgetting, the proposal is that the forget cue inhibits access to the original study context and thus impairs recall of the items studied in this context (Geiselman et al., 1983). Finally, in think/no-think impairment the assumption is that, during attempts to not let some memory contents enter consciousness, the memory representation of these contents is reduced so that accessibility is lowered when it comes to later retrieval (Anderson & Green, 2010). For an overview of the three inhibition proposals, see Bäuml et al. (2010).

This chapter discusses the possible role of inhibition in retrieval-induced forgetting and list-method directed forgetting. For each of these two forms of forgetting, the chapter introduces the experimental task employed to study the respective form of forgetting and the inhibition proposal entertained to explain the forgetting. Next, an overview of basic

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findings of each form of forgetting is provided, with a special emphasis on findings that the inhibition view can explain but which the prominent noninhibitory accounts can not easily explain. Then, for both forms of forgetting, shortcomings of the inhibitory view are discussed and challenges for future work on theoretical accounts of this forgetting are outlined. The chapter will end with some conclusions regarding the possible roles of inhibition in retrieval-induced forgetting and list-method directed forgetting.

RETRIEVAL-INDUCED FORGETTING

Experimental task and inhibition view on retrieval-induced forgetting

In recent years, retrieval-induced forgetting (RIF) has mostly been examined using the retrieval-practice task, which was first introduced by Anderson et al. (1994) into the literature. In this task, participants repeatedly retrieve a subset of previously studied material, to find out how retrieval practice influences later recall of the practised and unpractised material. Participants typically study exemplars from different semantic categories (e.g. FRUIT-*orange*, FRUIT-*banana*, FURNITURE-*table*), before, in a subsequent retrieval-practice phase, they are asked to repeatedly retrieve half of the exemplars from half of the categories using a word stem completion task (e.g. FRUIT-*or___*). Finally, recall of all initially studied exemplars is tested after some delay (see Figure 8.1a). The retrieval practice phase creates three types of items: practised items, unpractised items, and control items. Practised items refer to practised items from practised categories (*orange*), unpractised items refer to unpractised items from practised categories (*banana*), and control items refer to items from unpractised categories (*table*). Unsurprisingly, recall of the practised items is typically enhanced relative to the control items. The crucial RIF finding, however, is that recall of the unpractised items is usually impaired relative to control items on the later test (see Figure 8.1b). RIF is a very general phenomenon and has been observed over a wide range of materials and experimental settings (for recent reviews, see Storm et al., 2015; Bäuml & Kliegl, 2017).

The proposal that an inhibitory mechanism mediates the forgetting of the unpractised items plays a very prominent role in the RIF literature (see Storm et al., 2015; Bäuml & Kliegl, 2017). This proposal assumes that RIF arises because the memory representation of the unpractised items is inhibited during retrieval practice. In particular, the account suggests that during retrieval practice of some of the studied items, related unpractised items interfere and compete for conscious recall. To reduce the interference and facilitate selection of the to-be-practised items, the memory representation of the unpractised items is suppressed. For instance, when subjects are cued with FRUIT-*or___* during the retrieval-practice phase, other studied fruits, like *banana*, may come to mind and compete for conscious recall. To reduce the interference from *banana* the memory
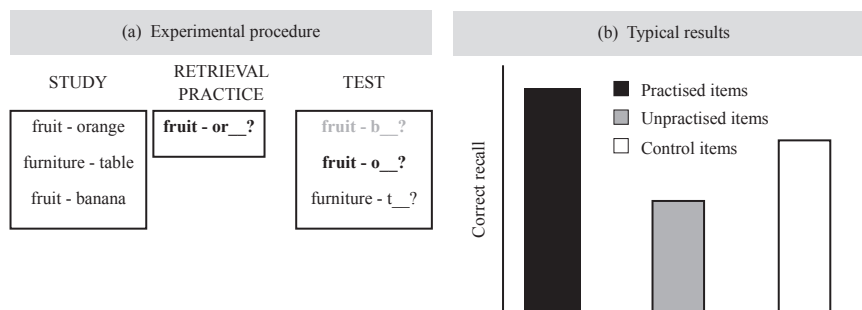
Figure 8.1   Retrieval-induced forgetting. a) Initially, participants study items from different semantic categories. In an ensuing retrieval-practice phase, only some of the items from some of the categories are repeatedly retrieved and thereby practised. On a final memory test, participants are asked to recall all items from the initial study phase. b) Practised items (e.g. fruit - orange) usually show enhanced recall, whereas unpractised items from the same practised categories (e.g. fruit - banana) show reduced recall relative to control items from categories that were not subject to retrieval practice (e.g. furniture - table).

representation of the item is suppressed, and, as a result, recall of that item on the subsequent final test is impaired.

CRITICAL RIF FINDINGS THAT INHIBITION CAN EXPLAIN

Testing format

The inhibition account assumes that suppression directly affects the representation of the unpractised items themselves, so that all retrieval routes to the inhibited item should become less effective and forgetting should therefore be observed across a wide range of memory tests. Research has largely confirmed this prediction, for instance showing that RIF occurs with category-cued recall and when category cues together with additional item-specific cues – like the items' unique initial letters or word stems – are exposed as retrieval cues at test (e.g. Anderson et al., 1994). But RIF has also been found in item recognition, both when using yes-no recognition testing (e.g. Hicks & Starns, 2004) and when using receiver-operating-characteristic analysis to examine whether selective retrieval impairs recognition of unpractised items (e.g. Spitzer & Bäuml, 2007).

Another suggestion arising from the view that RIF is due to inhibition is that RIF should still emerge when a novel test cue that was not present during study is provided at test.

Anderson and colleagues tested this cue-independence assumption by developing the independent-probe test. With this type of final test, an unpractised item (e.g. *banana*) is not tested with its original study cue (FRUIT-*b___*) but with a novel test cue (YELLOW-*b___*). The argument behind this procedure is that the presence of the novel retrieval cue may prevent participants from applying the original study cue to retrieve the practised item, thus bypassing possible retrieval competition arising from the practised items. A number of studies have examined the cue-independence assumption over the years, and the results from this research indicate that RIF can still arise when novel retrieval cues are employed at test (Anderson & Spellman, 1995; Weller et al., 2013). These findings provide support for the inhibition account of RIF.

Retrieval specificity

A further prediction of the inhibition account is that RIF should be retrieval specific, i.e. only a practice phase that involves active retrieval of previously studied items should reduce recall of the unpractised items, whereas passive restudy of the same material should not. The reason is that retrieval practice, but not restudy of the practised items, should induce interference and inhibition of the unpractised items. Early research addressing the issue used two variants of the retrieval-practice task, restudy and noncompetitive retrieval practice. In both variants, the to-be-practised items are re-exposed intact with the goal of strengthening the items' associations to their cue without inducing interference and inhibition of the unpractised items. When employing the restudy method, some of the originally studied category-item pairs are re-exposed (e.g. FRUIT-*orange*) and participants are asked to study the word pairs once again (e.g. Ciranni & Shimamura, 1999; Bäuml & Aslan, 2004). When employing the noncompetitive retrieval practice method, some of the originally studied items are re-exposed and participants are asked to recall the items' category label when the category's word stem is provided as a retrieval cue (e.g. FR___-*orange*; Anderson et al., 2000; Hanslmayr et al., 2010). The typical finding with these methods was that RIF arose in the (competitive) retrieval-practice condition, but no RIF-like impairment was observed following restudy or noncompetitive retrieval practice, which suggests that RIF is retrieval specific.

The influence of secondary tasks

In recent years, a number of studies have sought to determine the nature of the inhibitory mechanism supposed to mediate RIF. Anderson (2003), for instance, suggested that the type of inhibition that selective memory retrieval can trigger belongs to a more general family of executive processes that also operate to control overt behaviour or ignore irrelevant stimuli. In contrast, some other authors have championed the view that inhibition is mostly an automatic mechanism that acts whenever irrelevant information is

co-activated during attempts to retrieve relevant information by suppressing the irrelevant information (Conway & Fthenaki, 2003). Putting these two versions of the inhibition account to a test, Róman et al. (2009) reduced participants' attentional resources during the retrieval-practice phase with a secondary, concurrent updating task. The idea was that if the suppression mechanism underlying RIF needs executive control, then overloading attentional resources with a secondary task during retrieval practice should impair the action of the suppression mechanism and thus reduce RIF. On the other hand, if the suppression mechanism was mainly an automatic process, then overloading subjects' attention during retrieval practice should not affect RIF. The results showed that, relative to a standard retrieval-practice condition, there was no RIF effect when the secondary task was performed during retrieval practice, but there was reliable facilitation of the practised items. Overall, these findings align with the view that RIF requires attentional control, thus supporting the executive-control version of the inhibition account.

Neural correlates

Thus far, a number of studies have provided evidence for the inhibition account of RIF by examining neural correlates of the forgetting effect during the retrieval-practice phase. According to Anderson's (2003) executive-control version of the inhibition account, frontally mediated executive control processes should be recruited to suppress competing items during retrieval practice, so enhanced activation in such frontal areas during retrieval practice should be observable. Employing electrophysiological measures of brain activity (EEG), one study did find that stronger positivity over frontal electrodes was elicited in the retrieval-practice condition relative to a restudy condition, and the stronger positivity was correlated with the amount of RIF arising at the final test (Johansson et al., 2007). A more recent fMRI (functional Magnetic Resonance Imaging) study reported even more direct evidence for a critical role of inhibition in RIF, by demonstrating that selective retrieval practice measurably reactivates competing (unpractised) items and then progressively suppresses those interfering competitors (Wimber et al., 2015).

A few studies also searched for neural markers of RIF during the final memory test (Wimber et al., 2008; Spitzer et al., 2009). On the basis of the inhibition account, one might expect to find neural markers of RIF that reflect the suggested reduced memory strength signal of the unpractised items. One study found the retrieval of unpractised items to be associated with increased activation in the left anterior region of the ventro-lateral prefrontal cortex (Wimber et al., 2008). This finding is consistent with the inhibition account because prior neuroscientific work was able to demonstrate that increased activity in this region reflected the retrieval of weak memory traces (Badre & Wagner, 2007). Overall, the findings from both fMRI and EEG studies suggest that inhibitory processes operate during retrieval practice, inducing RIF at the final memory test.

Developmental findings

One prominent view in research on both cognitive development and cognitive aging is that inhibitory cognitive control capabilities are highly efficient in younger adults, but considerably less efficient in children and older adults (Hasher & Zacks, 1988; Bjorklund & Harnishfeger, 1990). Aslan and Bäuml (2010) examined RIF in kindergartners, second graders, and young adults, using both category-cued recall and item recognition. Results revealed that although all three age groups showed significant RIF in recall, only adults and second graders, but not kindergartners, showed forgetting in item recognition. Because inhibition-based RIF should be present in recall and recognition, these findings indicate that in adults and second graders, but not in kindergartners, RIF is mediated by (efficient) inhibition, supporting the proposal of an inhibitory deficit in kindergartners', but not school-aged children's, selective memory retrieval.

Prior research on RIF has provided evidence for an inhibitory deficit not only in preschool children, but also in adults above the age of 75 years. Aslan and Bäuml (2012) compared a group of 'young-old' adults (individuals between the ages of 60 and 75 years) with 'old-old' adults (individuals older than 75 years). They employed the retrieval-practice task with item recognition at test. Doing so, Aslan and Bäuml replicated earlier findings of intact RIF in the group of young-olds (e.g. Aslan et al., 2007; Ortega et al., 2012) but found an elimination of the effect in the group of old-olds, indicating that RIF may be a late-declining capability. Taken together, the findings from both children and older adults are in line with the proposal that inhibitory control processes mediate the forgetting. These control processes may develop during childhood, but then remain intact for most of the lifespan.

RIF FINDINGS THAT RETRIEVAL COMPETITION AND CONTEXT CHANGE CANNOT EASILY EXPLAIN

While the inhibition account assumes that RIF arises due to an inhibitory process that acts to overcome interference, the retrieval-competition and context-change accounts of RIF suggest that noninhibitory mechanisms underlie this form of forgetting.

Retrieval competition assumes that the associations between the practised items and their category cues are strengthened during retrieval practice, so that on the final test the (strengthened) practised items interfere and block access to the (non-strengthened) unpractised items, thus impairing memory for these items. For instance, successful retrieval of *orange* in the retrieval-practice phase may lead to a stronger association between *orange* and its category label FRUIT. When participants attempt to retrieve another initially studied exemplar from the category FRUIT on the final test (like *banana) orange* may then interfere and block successful recall of *banana*, thus creating RIF (Raaijmakers & Jakab, 2012).

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In contrast, the context-change account of RIF argues that the act of retrieval in the retrieval-practice phase introduces a shift in the subjects' internal context, creating distinct study and practice contexts. During the final test, subjects are then supposed to access the practice context when searching for the (practised and unpractised) items of the practised categories but access the study context when searching for the control items, so that due to the induced context change memory for the unpractised items may be impaired relative to the control items and RIF may arise (Jonker et al., 2013).

The finding that RIF arises over a wide range of final-test formats and is even present in item-recognition and independent-probe tests (e.g. Anderson & Spellman, 1995; Hicks & Starns, 2004) is hard to explain on the basis of the retrieval-competition account of RIF. Indeed, the account assumes that strengthening some exemplars through retrieval practice (e.g. FRUIT-*orange*) impairs the recall of related exemplars (e.g. FRUIT-*banana*) on a subsequent test because the presentation of their shared cue (FRUIT) causes the strengthened item (*orange*) to come to mind constantly and block the weaker item. Therefore, if RIF reflected the effects of retrieval competition, RIF should be present when the items' category cues are provided as retrieval cues at test. In contrast, RIF should be absent with item recognition or independent-probe testing, in which the effects of (strength-based) retrieval competition should be largely reduced if not eliminated (see Ratcliff et al., 1990; Rupprecht & Bäuml, 2016). The context account of RIF has been argued to be able to explain the presence of RIF in item recognition, at least when the recognition task is unspeeded (Jonker et al., 2013). The argument is that when the studied item *banana* is presented at test without its category label, participants reactivate the category label FRUIT together with the context in which the label was previously provided. In the case of practised categories (like FRUIT), this context may be the practice context, whereas for control categories, it may be the study context, thus inducing RIF. Although the context account may thus explain the presence of RIF in item recognition (but see Rupprecht & Bäuml, 2017), the account cannot explain the presence of RIF in independent-probe tests. Indeed, novel cues should eliminate the suggested context effects and thus eliminate RIF.

The demonstration that RIF arises after standard (competitive) retrieval practice but not after restudy practice (e.g. Ciranni & Shimamura, 1999; Bäuml & Aslan, 2004) and not after noncompetitive retrieval practice (e.g. Anderson et al., 2000; Hanslmayr et al., 2010) is also difficult to reconcile with the two noninhibitory accounts of RIF. On the basis of retrieval competition, standard retrieval practice, restudy practice, and noncompetitive retrieval practice should all strengthen the cue-item associations of the practised items, thus impairing recall of the unpractised items on the later memory test. The context account is challenged by the finding that noncompetitive retrieval practice does not induce RIF. Because retrieval practice should create a change in mental context regardless of whether the task is competitive or noncompetitive in nature, RIF should arise after both types of retrieval. The account, however, is consistent with the finding that no RIF arises after restudy practice because, unlike retrieval practice, restudy should not induce a change in mental context, thus precluding RIF.

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Roman et al.'s (2009) finding that a secondary task during the retrieval-practice phase can eliminate RIF is inconsistent with retrieval competition. Because, in this study, selective retrieval practice led to successful strengthening of the practised items regardless of whether attention was divided during retrieval practice or not, memory of the unpractised items at test should have been impaired both when the secondary task was present and when it was absent during practice. The finding can also not easily be explained by the context account. On the one hand, proponents of the account may argue that a secondary task can attenuate retrieval-induced context change, thus reducing or even eliminating RIF, which is what Roman et al. found. On the other hand, however, one might expect the presence of the secondary task to enhance the change in subjects' internal context and thus increase the size of RIF. In its current form, the account may be largely silent on this critical finding.

The observation that RIF is absent in preschool children and old-old adults (Aslan & Bäuml, 2010, 2012) is consistent with the inhibition account of RIF but is difficult to explain on the basis of retrieval competition. Because the two studies by Aslan and Bäuml found selective retrieval practice to induce successful strengthening of the practised items regardless of subjects' age levels, memory for the unpractised items should have been impaired on the final test in all these subject groups, which is not what the results showed. In contrast, the context account may be consistent with these developmental findings. Because previous work indicates that, in both younger children and older adults, memories are less well associated with context information than in young adults (Foley et al., 1983; Billingsley et al., 2002), one could argue that, when these two age groups attempt to retrieve an unpractised item on the final test (e.g., FRUIT-*o___*), the presentation of the category label FRUIT may trigger less of a tendency than in young adults to reinstate the context in which the label was last encountered (i.e. the practice context). Instead, these age groups may also recover the (more adequate) study context, which would reduce the RIF effect.

Possible shortcomings of and challenges for inhibition

While the inhibition account can explain a wide range of RIF findings, there are also findings that challenge the account. As was pointed out above, early findings consistently suggested that RIF exhibits retrieval specificity and arises in response to retrieval practice but not restudy trials (e.g. Ciranni & Shimamura, 1999; Anderson et al., 2000), which is well in line with the inhibition view. However, the results of more recent studies indicate that at least some re-exposure formats can induce RIF-like forgetting. Raaijmakers and Jakab (2012), for instance, employed a more demanding noncompetitive retrieval-practice task, in which the word stems of the category labels were absent during re-exposure (e.g., ___-*ball*) and exemplars with a relatively low frequency within their categories were used, which was supposed to enhance the strengthening of the associations between practised items and their category labels. Verde (2013) re-exposed

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studied category-exemplar pairs during practice but asked subjects questions about each single pair (e.g. '*Is the category presented the best to classify the exemplar?*'), again with the intention of strengthening category-exemplar associations. Finally, in Jonker et al. (2013), mental imagination tasks preceded the re-study trials to simulate context change as it may be induced by the retrieval process itself during retrieval practice. And, indeed, in all these cases, restudy impaired recall of the unpractised items, thus mimicking the typical RIF effect. These findings challenge retrieval specificity and therefore challenge the inhibition account. Rupprecht and Bäuml (2016, 2017) recently replicated all these findings but showed that the findings were restricted to recall testing. In fact, when item recognition was employed on the final test, (competitive) retrieval practice induced forgetting, whereas none of the employed reexposure formats did. Retrieval specificity thus seems to depend on testing format.

Another finding that is difficult to reconcile with the inhibition account is the observation that unpractised items seem to be shielded from the effects of retroactive interference. Abel and Bäuml (2014) employed a retrieval-practice task in which participants studied a categorised list and were then engaged in retrieval practice of some of the exemplars from some of the categories, before they were asked to learn a second categorised list, using the same categories as were employed in the first study list but with new category exemplars. The researchers found that the interpolated learning of the new category exemplars impaired recall of the control items, which replicates the standard finding of retroactive interference. In contrast, however, no such impairment arose for the recall of the practised and unpractised items, indicating that interpolated learning can reduce or even eliminate RIF. Arguably, on the basis of the inhibitory account, the unpractised items may be spared from interference effects because the learning of the related interpolated material may induce release processes on the inhibited information. While reexposure of the inhibited items following retrieval practice can diminish RIF (Storm et al., 2008), it is far from clear whether exposure of new, related material can induce the same release processes and thus eliminate the possible effects of retroactive interference.

The effects of prolonged delay on unpractised items constitute another puzzle for the inhibition account of RIF. Using retention intervals of 24 hours or longer between practice and test, a number of studies examined the role of prolonged delay for RIF. The results of the studies were mixed: while many studies reported intact RIF after the short delay but no RIF after the long delay (e.g. MacLeod & Macrae, 2001; Abel & Bäuml, 2014), a few other studies reported intact RIF also after the long delay (Garcia-Bajos et al., 2009; Storm et al., 2012). Interestingly, despite the difference in results, the findings from all these studies seem to converge on the pattern that the size of the RIF effect decreases with delay, with more time-dependent forgetting for the control items than the unpractised items (for a more extended discussion, see Bäuml & Kliegl, 2017). The role of retention interval for the unpractised items therefore shows a remarkable parallel to the role of retention interval for the practised items, which, both in the RIF studies and in studies on the testing effect (e.g. Roediger & Karpicke, 2006), typically show reduced time-dependent forgetting as well. As a whole, retrieval practice thus seems to insulate both practised and unpractised

items against the effects of time-dependent forgetting and retroactive interference. These findings impose important empirical restrictions on theories of RIF, challenging the inhibition account of RIF as well as all other current accounts.

Final remarks on the role of inhibition in RIF

Many findings in the RIF literature are in line with the proposal that RIF is mediated by inhibitory processes. This account assumes that during selective retrieval the not-to-be-retrieved items interfere and are inhibited to reduce this interference. Such inhibition is proposed to weaken the items' memory representation, so that memory for these items is impaired over a wide range of memory tests, which agrees with the empirical findings. The inhibition account is also consistent with the findings that RIF is often retrieval specific and disappears in the presence of secondary tasks, and it agrees with a number of further findings as well (see Storm et al., 2015; Bäuml & Kliegl, 2017). However, not all findings in the RIF literature can be explained by inhibition. In particular, the presence of RIF-like forgetting in recall tests when certain re-study formats are employed for practice disagrees with the account and may point to an additional role of retrieval competition in RIF (see Rupprecht & Bäuml, 2016, 2017).

Along these lines, a two-factor account of RIF has recently been suggested, which assumes that both inhibition and retrieval competition can contribute to RIF (Rupprecht & Bäuml, 2016; see also Anderson & Levy, 2007; Aslan & Bäuml, 2010; Schilling et al., 2014). This account assumes that inhibitory processes are triggered during retrieval practice and, in addition, retrieval competition can operate at test. While inhibition should induce a retrieval-specific reduction in the unpractised items' memory representation that can be measured over a wide range of memory tests, retrieval competition is assumed to not be retrieval specific and to play a role primarily in tests in which item-specific cues are reduced, like free recall or category-cued recall. In contrast, retrieval competition should hardly play a role in item recognition, in which the items themselves are presented as cues, and with independent-probe testing. Consequently, even though both inhibition and retrieval competition may contribute to RIF in general, the particular test format may influence the relative contributions of the two mechanisms.
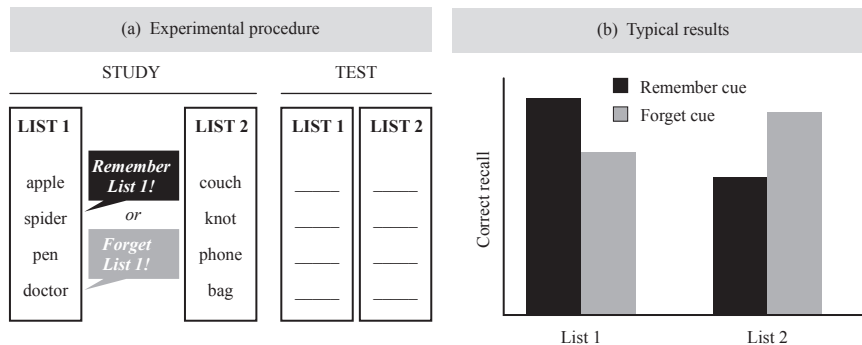
LIST-METHOD DIRECTED FORGETTING

Experimental task and inhibition view on list-method directed forgetting

In experiments on list-method directed forgetting (LMDF; Bjork, 1970, 1989), participants typically study two lists of items. Between study of the two lists, they are

either cued to remember the just studied first list for a later memory test (*remember condition*), or they are cued to forget the studied list – pretending that it was just presented for practice or by error (*forget condition*). In both conditions, participants are asked to memorise the second list, which is presented immediately after the remember cue or the forget cue were provided. After study of the second list, all participants recall *both* lists of items, irrespective of whether they received a remember or a forget cue for the first list (see Figure 8.2a). The results typically show two distinct effects of the forget cue relative to the remember cue condition: a recall impairment of list-1 items, often termed 'directed forgetting' of the first list items; and a recall improvement of list-2 items, often termed 'recall enhancement' of the second list items (see Figure 8.2b). Both effects of the forget cue are very general findings and have been demonstrated over a wide range of materials and experimental conditions (for reviews, see Bäuml et al., 2010; Sahakyan et al., 2013).

The proposal that an inhibitory mechanism mediates directed forgetting of list 1 items is one of the most discussed, and still current, theoretical accounts in the LMDF literature. The proposal assumes that a forget cue activates an inhibitory control process that reduces access to the list-1 study episode (Geiselman et al., 1983; Bjork, 1989). Thus, in contrast to RIF, inhibitory processes are not assumed to directly affect the memory representations of the single items but to impair retrieval routes to the whole list-1 study context. Such inhibition, for instance, might operate during list-2 encoding, when the previously studied list-1 items may get reactivated and interfere with the encoding of list-2 items (Conway

Figure 8.2 List-method directed forgetting. a) Participants study two lists of items and, after studying list 1, are either cued to keep on remembering the list for a later test or to try to forget the list, pretending that it would not be tested later. After study of list 2, all participants are asked to recall both previously studied lists, irrespective of which cue they received for list 1. b) Relative to participants who received a remember cue for list 1, participants who received a forget cue show reduced recall of list 1 and enhanced recall of list 2.

et al., 2000; Pastötter & Bäuml, 2007; Bäuml et al., 2008).[1] Critically, the inhibited access to list 1 can not only account for the reduced recall of list-1 items but can also accomodate the finding of the enhanced recall of list-2 items. Indeed, if the interference from list 1 is reduced after a forget cue has been provided, then recall of list-2 items should benefit and show higher recall in the forget condition than in the remember condition (see also Bjork & Bjork, 1996; Bäuml & Kliegl, 2013).

CRITICAL LMDF FINDINGS THAT INHIBITION CAN EXPLAIN

The role of the testing format

A central assumption of the inhibition account is that inhibition does not directly impair the representation of the to-be-forgotten items in memory, but reduces access to the whole list-1 study episode. This assumption suggests that the presence of list-1 forgetting should depend on the type of test used to assess memory. For instance, whereas in free recall, no retrieval cues are provided that can help reinstate the original study context, re-exposure of the list items during item recognition may reinstate context. Consistent with these expectations, list-1 forgetting has typically been found to be present with free recall testing (e.g. Bjork, 1989) and to also arise when weak item-specific cues, such as the items' unique initial letters, are provided as retrieval cues at test (e.g. Bäuml & Samenieh, 2010). In contrast, with recognition testing, list-1 forgetting has typically been found to be absent, both when using yes-no recognition testing (e.g. Geiselman et al., 1983) and when using receiver-operating-characteristic analysis to examine whether the forget cue influences recognition of the to-be-forgotten items (Pastötter et al., 2016). The findings on the role of testing format for LMDF are therefore consistent with the view that directed forgetting reflects reduced access to the original study context, a view compatible with the inhibition account of LMDF.

The role of list-2 encoding

Another finding of high relevance to the continuing theoretical debate on which cognitive mechanisms mediate LMDF is that list-1 forgetting depends on subsequent list-2 encoding. Following an original finding by Gelfand and Bjork (cited in Bjork, 1989), Pastötter and Bäuml (2007) varied whether, after study of list 1 and the presentation of the forget or

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[1] In its original version, the inhibition account is completely silent on exactly when the suggested inhibition processes should operate, thereby raising at least two possibilities: one possibility is that the proposed inhibitory processes may be activated immediately after the forget cue is provided, and the other possibility is that the proposed inhibitory processes may be activated later during encoding of the second list items.

remember cues, subjects were asked to study a second list of items or were engaged in an unrelated distractor task. Results showed list-1 forgetting when the second list had been studied, but did not show any forgetting of the first list when the second list had not been studied. In a follow-up study, Pastötter and Bäuml (2010) additionally showed that the amount of list-1 forgetting is directly related to the amount of list-2 encoding, i.e. the more items that are studied during list-2 encoding, the more pronounced the forgetting of list 1 is. These findings are consistent with the view that control processes unfold during list-2 encoding that reduce possible interference from list-1 items by inhibiting access to the whole list-1 study context. Importantly, the degree of the involvement of such control processes should depend on between-list interference: when there is no or only little interference arising from list 1 during study of list 2, no or only little cognitive control should be required and no list-1 forgetting should arise. Results by Conway et al. (2000) are consistent with this proposal.

The influence of secondary tasks

A natural prediction arising from the proposal that the mechanism mediating directed forgetting is inhibitory in nature, and relies on cognitive control and executive processes, is that its involvement should be resource-dependent. A few studies examined this proposal by introducing secondary tasks during list-2 encoding. If inhibitory control was resource dependent and operated during list-2 encoding, then secondary tasks during list-2 encoding should reduce the inhibitory control, thus attenuating list-1 forgetting. Macrae et al. (1997) were the first to address the issue, asking subjects to count vowels during the presentation of list-2 items. Conway et al. (2000) revisited the issue, asking subjects during list-2 encoding to keep in mind a list of digits. Both studies found the secondary task to reduce or even eliminate list-1 forgetting. These findings are consistent with the assumption of an inhibitory control process that is active during list-2 encoding and downregulates interference from intruding list-1 items.

Effects on incidental learning

Another prediction arising from the inihibition account of LMDF is that all contents that were encoded into memory during list-1 encoding should show directed forgetting, regardless of whether they were subject to the forget instruction or not. Indeed, according to inhibition, access to the study episode as a whole should be impaired, and thus all the contents that were part of this episode should show forgetting. In a seminal study by Geiselman et al. (1983), this prediction was put to the test by presenting intermixed study and judge items in each of the two item lists. For study items, subjects were asked to memorise them for a later test, but for judge items, subjects were merely asked to provide pleasantness ratings; in particular, subjects did not anticipate to be tested on these judge

items later. Intentionally encoded study items were generally remembered better than incidentally encoded judge items, but reduced recall of list 1 and enhanced recall of list 2 after the forget cue compared to the remember cue were nevertheless present for both item types (for a replication, see Abel & Bäuml, 2019). This finding is consistent with the view that the forget cue triggers inhibition of the whole list-1 study episode, not differentiating between an episode's intentionally and incidentally encoded contents.

Neural correlates

To date, two studies have been reported in the literature investigating the neural mechanisms underlying LMDF. Both studies measured neural correlates during list-2 encoding and thus were based on the view that the mechanisms mediating this form of forgetting operate during postcue encoding (Conway et al., 2000; Pastötter & Bäuml, 2007, 2010). Measuring EEGs and analysing subjects' oscillatory brain activity, Bäuml et al. (2008) found that the forget cue induces two effects relative to the remember cue condition: an increase in power and a decrease in phase coupling, both observed in the upper alpha frequency band (11–13 Hz). Whereas the increase in alpha power predicted the enhanced recall of list-2 items, the decrease in alpha phase coupling predicted the forgetting of list-1 items. Because phase coupling between electrode sites is often regarded a measure of the synchrony between distant neural assemblies and coherent firing between distant neuronal populations has been interpreted as a mechanism subserving binding processes, the decrease in alpha phase coupling could reflect the inhibitory unbinding of list-1 items and the deactivation of the retrieval routes to list 1.

In the second study, Hanslmayr et al. (2012) measured participants' brain activity by simultaneously recording EEG along with fMRI. EEG analysis again revealed a decrease in phase coupling in the upper alpha frequency band (11–13 Hz), whereas fMRI analysis additionally showed a simultaneous BOLD signal increase in the left prefrontal cortex. Moreover, direct repetitive Transcranial Magnetic Stimulation (rTMS) of the dorsolateral prefrontal cortex during list-2 encoding enhanced directed forgetting and phase desynchronisation, establishing a causal link between neural activity in the dorsolateral prefrontal cortex and list-1 forgetting. These findings go well with prior work on other forms of voluntary forgetting, which indicated that memory control may be mediated by the dorsolateral prefrontal cortex (see Anderson & Hanslmayr, 2014). Overall, the reports on neural correlates of LMDF are consistent with the view that frontally mediated executive control processes underlie directed forgetting.

Developmental findings

Following the view that cognitive control capabilities should be less efficient in children and older adults than in young adults (e.g. Hasher & Zacks, 1988; Bjorklund &

Harnishfeger, 1990), another line of research has examined directed forgetting across the lifespan. Regarding children, this work indicates that the mechanisms underlying directed forgetting seem to be maturing during childhood. In fact, several studies reported directed forgetting in older elementary school children, like fifth graders, that was indistinguishable in size from the forgetting in young adults, whereas the directed forgetting in younger elementary school children, like first graders, was reduced or even eliminated (e.g. Harnishfeger & Pope, 1996; Aslan et al., 2010). This holds while first graders may also show typical LMDF – but only if a forget cue is employed that places very high emphasis on the need to forget (see Aslan et al., 2010a).

Regarding older adults, results indicate that the mechanisms mediating directed forgetting remain rather stable across large parts of adulthood. Comparing LMDF in younger adults with LMDF in older adults with an age range between 65 and 75 years, results consistently showed directed forgetting in older adults that was comparable in size to that in young adults (Sego et al., 2006; Zellner & Bäuml, 2006). Above 75 years of age, however, older adults' directed forgetting seems to dissipate. Consistent with this view, Aslan and Bäuml (2013) reported typical LMDF in young-old adults (up to 75 years) but reduced LMDF in old-old adults (above 75 years). LMDF thus seems to be a late-declining capability. Taken together, the findings from both young children and older adults are in line with the proposal that inhibitory control processes mediate the forgetting. These control processes may evolve during middle childhood, but then remain intact for most of the lifespan, only becoming inefficient when we reach very old age.

LMDF FINDINGS THAT CONTEXT CHANGE CANNOT EASILY EXPLAIN

The inhibition account of LMDF assumes that directed forgetting is due to the involvement of an inhibitory control process that downregulates the interference from list 1 by inhibiting access to the list as a whole. In contrast, the context-change account of LMDF assumes that the forget cue induces a change in people's mental context after study of list 1. This context change should lead to a mismatch between the context present at test and the context present during list-1 study, which should reduce recall of list-1 items (Sahakyan & Kelley, 2002). Like inhibition, this account provides not only an explanation of list-1 forgetting, but can also explain list-2 enhancement. Indeed, because the suggested reduced access to list 1 should decrease the list's interference potential during recall of list-2 items, not only list-1 forgetting but also list-2 enhancement should arise.

The finding that LMDF arises mostly in free recall and cued recall but not in item recognition tests (e.g. Geiselman et al., 1983) is not easily explained on the basis of the context change view of LMDF. The reason is that results on the effects of context change in item recognition in the literature are mixed. Whereas some context change studies reported evidence for context effects in item recognition (e.g. Bodner & Lindsay, 2003),

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other studies did not find any reduction in recognition performance after context change (e.g. Smith et al. 1978). Apparently, the circumstances that surround a context change determine whether context change reduces item recognition. What exactly the circumstances in LMDF are that may prevent the forgetting of list-1 items to show up in item recognition is unclear to date.

The finding that list-2 encoding is a necessary precondition for directed forgetting to arise, together with the finding that the amount of forgetting increases with the amount of postcue encoding (Pastötter & Bäuml, 2007, 2010), provide another challenge for the context-change account. The reason is that, in a number of classic context-change studies, manipulations that decreased access to study context at test have been shown to reduce recall even in the absence of further encoding after the context change (e.g. Godden & Baddeley, 1975; Smith et al., 1978). On the other hand, when relatively weak context change manipulations had been used, like simple room changes or manipulations of internal states, such as mood induction, context change sometimes failed to induce a context effect (e.g. Eich, 1985; Fernandez & Glenberg, 1985). Mental context change as induced by a forget cue may thus represent such weak context change, requiring subsequent learning of further material to enhance the contextual effect. Results from Pastötter and Bäuml (2007) showing context-dependent forgetting, as induced by a mental context change task, in the presence but not the absence of subsequent encoding, are consistent with such a proposal.

The finding that secondary tasks during list-2 encoding can reduce or even eliminate directed forgetting (Macrae et al., 1997; Conway et al., 2000) is also not easily explained by the context-change account. Indeed, if the forget cue triggered mental context change, what exactly happens subsequent to the context change might not matter much, and list-1 forgetting might arise regardless of whether attention was divided during list-2 encoding or not. Alternatively, one may argue that secondary tasks may well influence context change. For instance, the encoding of the list-2 context may require attentional resources, and when these resources are taxed by a secondary task, context encoding may become less efficient, thus reducing the contextual change and the forgetting of list-1 items (e.g. Sahakyan et al., 2013). In contrast, the presence of the secondary task might create further context change on its own regardless of whether there was prior forget cue-induced context change or not, in which case list-1 forgetting would not depend much on the presence of the secondary task. Obviously, in its current form, the context change account is largely silent on the possible role of secondary tasks in LMDF.

Probably the currently strongest challenge for the context-change account of LMDF is provided by the recent finding that list-1 forgetting is lasting (Abel & Bäuml, 2017, 2019). Indeed, it is a relatively straightforward prediction of the context-change account that LMDF should not be lasting. The reason is that internal context is generally assumed to change over time (e.g. Estes, 1955; Bower, 1972), so that experimentally-induced context change should lose much of its relevance when the retention interval between study and test is prolonged and mental context thus has changed due to the sheer passage of time. Results by Divis and Benjamin (2014) provide direct support for this claim by showing that context change effects can be present immediately after study but be absent

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15 min later. Against this background, the findings of Abel and Bäuml (2017, 2019) on the persistency of LMDF are important. These researchers conceptually replicated Divis and Benjamin's (2014) result that context change effects are transient, reporting intact context-dependent forgetting after a 3-minute retention interval but no forgetting after a prolonged retention interval of 20 minutes. More important, Abel and Bäuml showed that a forget cue can create forgetting that is still present after delays of 20 minutes and even 24 hours. Critically, the difference in results between context-dependent forgetting and directed forgetting after prolonged retention interval arose, although the two forms of forgetting showed equivalent forgetting after the short 3-minute retention interval. These findings are clearly at odds with the context-change account of LMDF.

Possible shortcomings of and challenges for inhibition

While the inhibition account is basically consistent with a wide range of LMDF findings, a general critique of advocates of noninhibitory accounts of LMDF is that the account suffers from conceptual shortcomings and a certain degree of theoretical vagueness. Indeed, in itself the account makes relatively few specific predictions that can be tested directly, and quite often the account provides a posthoc explanation of findings only. One example is the issue of when exactly inhibition in this paradigm operates. As mentioned above, a priori there are at least two possibilities, and inhibition may operate immediately after the forget cue is provided or inhibition may operate later during list-2 encoding. It is the finding that LMDF presupposes list-2 encoding (e.g. Pastötter & Bäuml, 2007, 2010) which indicates that inhibition may operate during list-2 encoding. Another example is the issue of whether LMDF is transient or persistent. In its original version, the account makes no prediction on the issue at all. It is the finding of persistent LMDF which suggests that inhibition should be assumed to be lasting (for a discussion, see Abel & Bäuml, 2019). Obviously, the concept of inhibition in LMDF is still underspecified and requires further conceptual work in order to create a larger number of specific predictions.

Like the context-change account of LMDF, the inhibition account assumes that list-1 forgetting and list-2 enhancement are the two sides of the same coin. Because the forget cue reduces the accessibility of list-1 items, interference of list 1 during list-2 recall should be reduced and recall of list-2 items should thus be enhanced. However, results from a number of studies have shown that the two effects of the forget cue do not always arise together. Accordingly, list-1 forgetting has been found in the absence of list-2 enhancement, and list-2 enhancement has been found in the absence of list-1 forgetting (e.g. Sahakyan & Delaney, 2003; Benjamin, 2006; Pastötter & Bäuml, 2010; Aslan & Bäuml, 2013). As a result, it has been suggested that the two effects of the forget cue might be partly mediated by different mechanisms, with the forgetting being caused by inhibition or context change, and the enhancement being mediated by (additional) improved encoding. Sahakyan and Delaney (2003), for instance, suggested that list-2 enhancement might be due to a switch to more efficient encoding strategies from list 1 to list 2. Pastötter and Bäuml (2010)

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argued that encoding efficiency decreases with increasing amounts of incoming information, and the forget cue then prompts a reset of the encoding process for list-2 items. In both cases, the inhibition account would have to be complemented with a second (encoding) mechanism in order to be able to explain the findings of dissociations between list-1 forgetting and list-2 enhancement.

Another challenge for the inhibition account of LMDF is provided by Lehman and Malmberg's (2009) finding that LMDF as it occurs in the original (2-list) task differs from LMDF as it occurs in a 3-list variant of the task. In the 3-list variant, before studying lists 1 and 2, subjects study an additional list (list 0), and after study of list 0 and list 1 are then cued to either remember or forget the two previous lists.[2] Unfortunately, LMDF in the 3-list task differs fundamentally from LMDF in the 2-list task. Above all, when using the 3-list task, the forgetting of list-1 items is present in item recognition, whereas it is typically absent in the 2-list task (for further dissociations between tasks, see Abel & Bäuml, 2019). This finding provides a challenge to the inhibition account, which assumes that the forgetting should be absent in item recognition. Why results seem to change from the 2-list task to the 3-list task is an open issue. Getting an answer on this issue is important and may inform us on whether different mechanisms mediate the forgetting in the two types of tasks.

Final remarks on the role of inhibition in LMDF

Many findings in the LMDF literature are consistent with the proposal that LMDF is mediated by inhibitory processes. The inhibition account assumes that a cue to forget no-longer-relevant information activates a cognitive control process that reduces access to the respective study episode, and thereby downregulates the outdated information's interference potential. Critically, such inhibition is assumed to impair retrieval routes to the original episode but to not impair the memory representation of the single items. Consistently, LMDF is reliably observed on recall tests, but is usually absent on item recognition tests. On the basis of the proposal that inhibition operates during postcue encoding, the inhibition account is in line with the finding that list-1 forgetting depends on list-2 encoding and disappears when secondary tasks are introduced during list-2 encoding, as well as a number of further findings in the literature (see Bäuml et al., 2010; Sahakyan et al., 2013). Yet not all findings are easily explained by inhibition. Above all, the account suffers from conceptual shortcomings, which reduce the account's predictive power.

Accounts of LMDF are typically single-mechanism accounts and assume that list-1 forgetting and list-2 enhancement are mediated by the same cognitive mechanism. This is also true for inhibition. Results on dissociations between list-1 forgetting and list-2 enhancement challenge this view and thus also challenge inhibition. They indicate that

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[2] This task was introduced by Lehman and Malmberg to reduce possible unwanted advantages of list 1 over list 2, which, according to the authors, may occur in the 2-list task.

an additional encoding mechanism may contribute to list-2 enhancement, as is reflected in current two-mechanisms accounts of LMDF, which assume that inhibition or context change mediate list-1 forgetting and an additional encoding mechanism contributes to list-2 enhancement. Whether the contribution of the encoding mechanism reflects a change in encoding strategy (Sahakyan & Delaney, 2003) or some reset of the encoding process (Pastötter & Bäuml, 2010) is an open issue that requires further research.

CONCLUSIONS

Retrieval competition and context change can explain a wide range of forgetting findings, including retroactive interference, proactive interference, time-dependent forgetting, and context-dependent forgetting. Although it has been argued that the two cognitive mechanisms can also explain RIF and LMDF – and, in concert, may even serve as a complete explanation of episodic forgetting – there is evidence that this is not the case and that neither of the two mechanisms can (easily) explain the whole range of RIF and LMDF findings. For instance, regarding RIF, both retrieval competition and context change are challenged by the findings that (i) RIF arises in item recognition and independent-probe tests, (ii) RIF can be retrieval specific, with selective retrieval (but not selective restudy) impairing recall of nonrepeated items, and (iii) RIF disappears when there is a secondary task during selective memory retrieval, although the secondary task does not affect recall of the practised items. Regarding LMDF, context change has problems to explain why (i) changes in internal context induce transient forgetting whereas a forget cue induces lasting forgetting, (ii) postcue encoding is critical for the forgetting of precue items, and (iii) a secondary task during second list encoding eliminates the forgetting of first list items. Thus, other cognitive mechanisms may operate to induce RIF and LMDF.

Indeed, there is evidence that inhibitory processes contribute to RIF and LMDF. The assumption that selective retrieval induces inhibition of nonretrieved items, for instance, can explain why (i) RIF arises over a wide range of memory tasks and is not restricted to recall tests, (ii) RIF can be retrieval specific, and (iii) RIF disappears in the presence of a secondary task. Similarly, the assumption that a forget cue inhibits access to the original study context in LMDF may explain why (i) the forgetting of to-be-forgotten items is lasting but forgetting induced by context change is not, (ii) there is a critical role of postcue encoding for the forgetting of precue items, and (iii) directed forgetting disappears in the presence of a secondary task.

However, although it is likely that inhibition contributes to RIF, there is also evidence that inhibition alone can not capture the whole range of RIF findings, as, for instance, is demonstrated by the fact that retrieval specificity typically arises in item recognition but can be absent in recall tests. Multiple mechanisms may thus underlie this form of forgetting, and a two-mechanisms account, which assumes a role of both inhibition and retrieval competition in this form of forgetting, indeed seems to be able to explain a wide range of RIF findings. Whether this account is sufficient to explain RIF, or needs the

inclusion of further mechanisms like context change, is unclear to date and awaits future examination.

With regard to LMDF, inhibition may be able to account for a wide range of LMDF findings, but this holds only if inhibition is assumed to be long lasting and to operate during postcue encoding. Both assumptions are posthoc inclusions into the original version of the account and, clearly, further empirical work is required to see whether these assumptions really hold. Until then, the status of the inhibition account of LMDF remains somewhat unclear as does the answer to the question of whether multiple mechanisms may mediate LMDF, for instance, with inhibition operating in some situations (or individuals) and context change in others. Understanding the exact role of inhibition in episodic forgetting remains a challenge for future studies.

Further Reading

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