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Retrieval-Induced Forgetting in Recall: Competitor Interference Revisited

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Participants studied category–exemplar pairs (*FRUIT Cherry*, *FRUIT Grape*) and then practiced some of the items (*Cherry*). In Experiment 1, practice that involved retrieving the item from memory suppressed recall of related items (*Grape*), a finding known as the retrieval-induced forgetting (RIF) effect. In Experiment 2, practice that involved studying the item without retrieval produced no RIF effect. Both retrieval and nonretrieval practice facilitated the subsequent recall of practiced items (*Cherry*). The dissociation between "strengthening" of practiced items and forgetting of related items is thought to be evidence that RIF is the result of inhibition during earlier retrieval attempts rather than interference from competing memories at retrieval. However, simulations of the SAM-REM model show that competitor interference can account for this dissociation. Experiments 3–6 supported the predictions of the model by demonstrating that nonretrieval practice can produce the RIF effect under conditions that emphasize context encoding or increase the number of competitors.

Keywords: memory, recall, forgetting, retrieval-induced forgetting, memory models

We retrieve memories with incredible speed and accuracy, considering the breadth of stored experience at our disposal. Nevertheless, the difficulty of isolating a single memory among all accessible memories is such that our attempts at retrieval sometimes end in failure. Most theories of recall assume that interference from other memories is an important factor in forgetting. However, the mechanism by which interference leads to retrieval failure remains a matter of debate. Interference theories of the last century (see Postman, 1976, for a review) viewed forgetting as a consequence of the associative structure of memory. Contemporary theories of recall in this tradition suggest that forgetting results directly from competition among the associates of a cue. When a retrieval cue activates multiple associated memories, competition for retrieval interferes with the ability to recall the intended target. For example, our inability to remember what we did Wednesday night might be due to an abundance of other memories that spring to mind when we think about the past week. In the laboratory, interference is typically examined with paired associate paradigms. Imagine studying a series of word pairs (*FRUIT Cherry*, *FRUIT Grape*) where multiple retrieval targets are associated with a single cue. Later, one of the targets must be recalled given the cue (*FRUIT C_?*). According to competitor interference, the cue will activate both associates (*Cherry*, *Grape*), which then compete for retrieval. This competition reduces the likelihood of successfully recalling the intended target (*Cherry*).

An influential alternative view is offered by Anderson, Bjork, and Bjork's (1994; Anderson & Bjork, 1994) inhibition theory of forgetting, which suggests that competition among memories is not the primary cause of retrieval failure.[1] Rather, memories are made inaccessible by inhibitory mechanisms that are active during the retrieval process. In order to facilitate the recall of an intended target, nontarget memories associated with the cue are inhibited, making them more difficult to subsequently recall. As Anderson (2003) put it: "It is the executive control mechanism that overcomes interference—inhibition—that causes us to forget, not the competition itself. . . . The mere storage of interfering traces is not what causes memories to grow less accessible with time" (p. 416).

Inhibition theory takes as a premise that competition within the associative network of a cue is problematic. It departs from traditional interference theories in suggesting that competition by itself is normally not responsible for retrieval failure in recall. As detailed in the next section, competitor interference is sufficient in theory to account for forgetting in paired associate paradigms. Why is there a need for an additional mechanism? The case for inhibition is based in part on an appeal to plausibility. Inhibition plays a fundamental role in neuronal processing, and many theorists point to its presence in a variety of higher level, cognitive domains (e.g., Dagenbach & Carr, 1994; MacLeod, 2007). Anderson and colleagues have argued eloquently that the ability to inhibit memories is beneficial in many situations, from the conscious avoidance of traumatic reminiscences to the suppression of competition at a preconscious level (Anderson, 2003; Anderson & Huddleston, 2011).

More important, the case for inhibition is supported by a number of key findings, drawn mainly from investigations of retrieval-induced forgetting (RIF) in which recalling an item tends to suppress the availability of other items in memory. This has been studied with the retrieval practice paradigm introduced by Anderson

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[1] Many investigators have since contributed to the development of inhibition theory. Although these investigators do not espouse identical views, the view expressed by Anderson and colleagues (Anderson, 2003; Anderson et al., 1994) and described here is the most well articulated and represents standard thinking in the literature.

son et al. (1994). The basic paradigm consists of three consecutive phases: study, practice, and test. The study phase involves encoding a number of paired associates, each belonging to one of several categories (*FRUIT Cherry, FRUIT Grape, TOOL Hammer, TOOL Pliers*). During the practice phase, half of the items from some of categories (P+ items) are tested with cued recall (*FRUIT C_?*). Finally, during the test phase all of the studied items from both practiced and nonpracticed categories are tested for recall. The typical finding is that nonpracticed items from practiced categories (P− items; *FRUIT G_?*) are recalled at a lower rate than items from nonpracticed categories (NP items; *TOOL H_?*). The reduction in P− relative to NP recall will be referred to as the RIF effect (although, as will be seen, the effect sometimes emerges even when no retrieval occurs during the practice phase). According to the inhibition account, recalling *Cherry* during the practice phase leads to inhibition of other associates of the cue *FRUIT,* such as *Grape*, making them more difficult to recall during the final test.

Competitor Interference and RIF

There are a variety of ways that interference theories might account for RIF (Anderson & Bjork, 1994). The present study focuses on the mechanism most often discussed in the RIF literature: competitor blocking. There is a tradition of describing recall as a search through related memories (e.g., James, 1890). Modern theories often model this search as a stochastic process (Raaijmakers & Shiffrin, 1980; Rundus, 1973; Shiffrin, 1970; Wixted & Rohrer, 1994) where the probability of retrieving memory image j depends on the likelihood ratio

$$P(j \mid cue) = \frac{A_j}{\sum A_k}, \text{where } k = 1 \ldots n. \tag{1}$$

The numerator describes the association strength between the cue and image j, and the denominator describes the summed association strengths between the cue and all n images in the search set. The degree of competitor interference depends on the associative strengths of nontarget images in the denominator. As the value of the denominator increases, the likelihood of retrieving the intended target decreases. Assuming that only one image can be retrieved per attempt and that the number of attempts is limited, increasing the denominator effectively blocks retrieval of the target memory.

If the cue is equally associated with all items in the search set, the likelihood of retrieving the intended target is $1/n$. In this case, interference is determined solely by the number of nontarget items in the set. If association strength varies, the strength of the target relative to nontargets also becomes a factor. Interference increases as the strength of competitors increases. In short, any increase in the number or strength of competitors will have a negative impact on recall of the target. Competitor interference predicts that forgetting should be number dependent and strength dependent.

Inhibition theory, on the other hand, predicts that forgetting should be retrieval dependent but strength independent. The purpose of the inhibitory mechanism is to aid retrieval by suppressing competitors. Therefore, the act of retrieving P+ items during the practice phase is critical to producing the RIF effect. If P+ items are practiced in a way that does not require their retrieval, there should be no need to inhibit competitors and no RIF. In contrast, competitor interference predicts that any practice of P+ items that increases their association strength will have an adverse effect on memory for competitors. A straightforward way to test these opposing predictions is to manipulate the task used during the practice phase. Many studies have found that although recalling P+ items during practice reduces the ability to recall competitors, presenting P+ items for additional study does not (Anderson & Bell, 2001; Bäuml, 2002; Campbell & Phenix, 2009; Ciranni & Shimamura, 1999; Gómez-Ariza, Fernandez, & Bajo, 2012; Hulbert, Shivde, & Anderson, 2012; Johansson, Aslan, Bäuml, Gäbel, & Mecklinger, 2007; Staudigl, Hanslmayr, & Bäuml, 2010; Wimber, Rutschmann, Greenlee, & Bäuml, 2009).[2] The finding is consistent with the retrieval dependence prediction of inhibition.

Additional study of P+ items during the practice phase does enhance their subsequent recall in the final test, often to the same extent as retrieval practice. In other words, additional study apparently strengthens P+ items while having no discernible effect on other items, inconsistent with the strength dependence prediction of competitor interference. The absence of RIF following nonretrieval practice, combined with observations that retrieval can impair competitor recall even when no studied item is strengthened (Bäuml, 2002; Storm, Bjork, Bjork, & Nestojko, 2006), has led to a consensus in the RIF literature summarized by Bäuml (2006): “Retrieval-induced forgetting studies point to retrieval inhibition rather than any variants of (strength-dependent) competition as the major source of the recall impairment” (p. 563). The conclusion that the apparent strength independence of RIF is uniquely consistent with an inhibitory mechanism constitutes one of the main arguments for inhibition and against competitor interference (Anderson, 2003).

A recent review by Storm and Levy (2012) noted that nearly 200 studies have investigated RIF over the last two decades. The influence of inhibition theory on thinking about recall derives not only from its ability to explain findings from this large literature but from the seeming inability of competitor interference to do so. It is proposed here that the theoretical treatment of competitor interference in the RIF literature has been inadequate. Using the SAM-REM model of recall (Malmberg & Shiffrin, 2005) to illustrate the strength-dependent and number-dependent properties of competitor interference, I will show that such a model can accommodate findings in the RIF literature thought to be inconsistent with strength-dependent forgetting. The discussion will turn first to how the strength-dependent properties of the model, paired with testable assumptions about how information is encoded during practice, might account for dissociations between strengthening and forgetting. It will then consider how the number-dependent properties of the model might account for RIF in the absence of competitor strengthening.

[2] Other studies, in the list-strength effect literature, do report that strengthening some items in a study list via repetition, increased study duration, and so on has a negative effect on recall of other studied items (e.g., Malmberg & Shiffrin, 2005; Ratcliff, Clark, & Shiffrin, 1990; Tulving & Hastie, 1972; Wixted, Ghadisha, & Vera, 1997). However, these studies have primarily used free recall, a task in which output order is not controlled. Because strong items tend to be recalled earlier, a reduction in weak item recall could be due to retrieval inhibition from previously retrieved strong items rather than to increased competition from strong items. The conflation of memory strength and exposure to retrieval inhibition makes it difficult to draw conclusions about strength independence from this prior work (cf. Verde, 2009).

Modeling Strength and Retrieval

The portrayal of competitor interference in the RIF literature commonly makes reference to a model proposed by Rundus (1973). In this model, search involves sampling items with replacement from memory. The probability of recalling a given memory depends on the strength of its association with the cue, relative to the association strengths of all other memories in the search set, as described by the likelihood ratio in Equation 1. The search is terminated following a number of consecutive failures to sample a memory that has yet to be recalled. The model can be extended to situations where a cue specifies a single target (*FRUIT G_?*) by assuming that a search is terminated following a number of failed attempts to sample the intended target due to repeated sampling of nontargets. In the Rundus model, increasing the association strength of competitors interferes with the sampling of a target.

What does it mean to "strengthen" a memory? In the RIF literature, strength is defined operationally as the ability to recall an item. Retrieval and additional study are both said to strengthen a practiced item because both forms of practice enhance subsequent recall. Note that "strengthening" here means strengthening the association between the cue and the practiced item (were this not true, the Rundus model would not predict interference). The direct correspondence between association strength and recallability might be consistent with a relatively simple model like the one proposed by Rundus, but it is not a necessary characteristic of competitor interference models generally. What this means is that a dissociation between the ability to recall an item and the tendency for that item to interfere with competitors is not incompatible with competitor interference.

This point will be illustrated with a more complex interference model, the SAM-REM model described by Malmberg and Shiffrin (2005). The model combines core elements from two parent models. SAM is a general model of recall (Mensink & Raaijmakers, 1988; Raaijmakers & Shiffrin, 1980, 1981) that has been applied successfully to a wide range of phenomena. REM (Shiffrin & Steyvers, 1997) models the encoding and matching of multidimensional memory representations. Broadly speaking, the implementation of SAM-REM described below can account for dissociations between recallability and interference because the model possesses two properties. First, different types of information can be stored depending on the encoding task. Second, different types of information contribute in different ways to retrieval and interference. It should be emphasized that the purpose of this discussion is not to advocate specifically for SAM-REM but instead to show that a competitor interference model with these two basic properties can account for the apparently strength-independent findings reported in studies of RIF.

The Rundus model portrays memory representation in a rudimentary fashion. Most theorists would agree, however, that representations are complex and multidimensional. A nuanced view of memory representation is important for understanding the relationship between strength and interference. A common distinction is made between item and context features (Humphreys, 1978; Murnane, Phelps, & Malmberg, 1999). Item features are those of the object itself, but context features include details of the surroundings, associations with other objects, and emergent properties of object groupings. In SAM-REM, memories are represented as vectors of features, with each feature denoted by a numerical value. The stimuli in RIF studies consist of cue–target pairs. Typically (and in the experiments to follow), each stimulus is a category–exemplar pair (*FRUIT Cherry*) where the category name will eventually serve as the retrieval cue for recall of the target exemplar. In the present implementation, each memory image is represented as a vector of 20 context features and 20 item features. Item information represents features of the exemplar (*Cherry*). Context information represents the local context, defined as the features of the category (*FRUIT*).[3]

When a probe is presented for study, its feature values are copied into a memory vector. At each time interval, there is a probability u^* of storing a value for each feature. The process is gradual and prone to error, so that the resulting memory image is an incomplete version of the original probe. It is assumed that depth of processing and attention mediate the storage of information. For example, an elaborative encoding task might enhance feature storage more than would a shallow task. Similarly, an encoding task that draws particular attention to context information might lead to the preferential storage of context features. These effects are modeled by varying the u^* parameter to reflect the rate of feature storage. Here, context and item features are assigned separate values (u^*_c and u^*_i, respectively). The simulations below will show that varying the effect of encoding on u^*_c and u^*_i can produce both the presence and the absence of a RIF effect.

SAM-REM describes recall as a two-stage process of sampling and recovery. First, a memory image is sampled with replacement from the search set. The probability of sampling the target j depends on the likelihood ratio

$$P(j \mid cue) = \frac{\lambda_j}{\sum \lambda}. \tag{2}$$

The variable λ signifies the degree to which the features of the probe match the features of an image in memory. The numerator represents the match to image j, and the denominator represents the summed matches to all images in the search set. This is the basic competition model of Equation 1. After an image is sampled, an attempt is made to recover it to an extent that it can be physically produced. This is a function of the number of correctly stored feature values in the relevant portion of the image. The sampling and recovery process continues until an appropriate target is produced or a criterion number of failed attempts leads to termination of the search.

Consider a cued recall task where the category context is supplied as a cue (*FRUIT C_?*). During the sampling stage, the probe consists mainly of the context features (with a few item features from the initial letter of the target). Competitor interference occurs at this stage and is mainly a function of the degree to which context features (*FRUIT*) have been stored and match those of the probe and other memories. In the cued recall task, only the target exemplar has to be produced. Therefore, the probability of recovering the target (*Cherry*) is a function of the number of correctly stored

[3] Other aspects of context, such as global or environmental context, were not modeled. This simplification does not alter the conclusions of the simulations (see the Appendix).

item features. Recovery does not depend on the state of other images in memory. In summary, successful recall requires that a target is both sampled and recovered. Sampling depends mainly on context features and is prone to interference from other memories that share the context. Recovery depends solely on item features and is immune to interference.

As an illustration of these points, a simplification of SAM-REM is shown in Figure 1. The probe and memory vectors each consist of 16 features, eight representing category context information and eight representing item information. Imperfect encoding is assumed; memory vectors have some null feature values where information has yet to be stored. A matching value (λ) is calculated for each memory image by comparing the probe to the image, feature by feature. Matching features increase λ, and mismatching features decrease λ. The probe (*FRUIT C_?*) most closely matches the target image A (*FRUIT Cherry*) but also matches image B (*FRUIT Grape*) to a moderate degree. It matches images C (*TOOL Hammer*) and D (*TOOL Pliers*) to a low degree. Because the denominator of Equation 2 is based on summed λ, all images contribute to interference, meaning they all have an effect on the probability of sampling target image A. This probability would decrease if additional images were added to the search set. Thus, interference is number dependent. Also, because of its greater match to the probe, image B contributes more to the denominator of Equation 2 than do images C and D. Thus, interference is strength dependent, if strength is defined in terms of the number and value of stored features.

Imagine that image B was given additional encoding, as would happen during practice. This would result in the storage of additional category context and item features where there had previously been null values. The storage of context features would increase the likelihood of image B being sampled given the probe *FRUIT*. This would improve its own recallability given the probe *FRUIT G_?* but would also increase its interference with image A

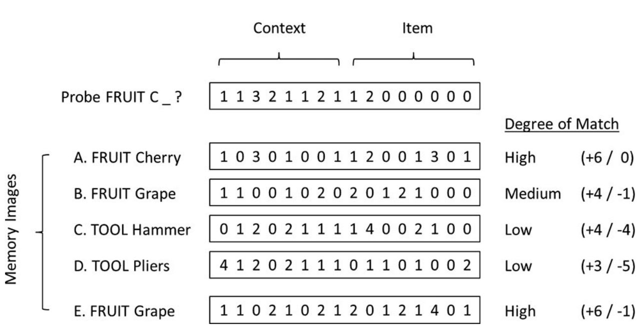

Figure 1. In SAM-REM, each stimulus probe and memory image is represented by a vector of features (in this example, eight context and eight item features). A nonzero feature value indicates stored information, and a zero value indicates none has been stored. The context features of the probe *FRUIT C_?* are identical to those stored (incompletely) in images A, B, and E. The probe also contains two item features of the word stem. The matching value (λ) of the probe to each image is a function of the number and value of each stored feature. The description to the right of each image vector indicates relative match (high, medium, low) to the probe, based on the number of matching (+) and mismatching (-) stored features. Image E is a version of image B that has had additional encoding, increasing the number of stored features. The details of the model are simplified in this example (see Appendix for full description).

given the probe *FRUIT C_?* The storage of item features would improve the recovery of image B following sampling but would have little effect on the sampling of image A, because item features are largely absent from the probe. The differential contribution of context and item features to sampling and recovery allow the model to produce a dissociation between recallability and interference like that observed in studies of RIF.

The idea that the encoding of item or context features might vary depending on the nature of the practice task will be referred to as the differential encoding hypothesis. Practice that selectively enhances the encoding of category context features will facilitate recall of P+ items and interfere with recall of P− items. On the other hand, practice that selectively enhances the encoding of item features will facilitate recall of P+ items but not interfere with recall of P− items. The facilitation of P+ items could be identical in the two cases, although this is not necessary. All of these points are illustrated in the model simulations to follow.

Model Simulations

Monte Carlo simulations were run with the implementation of SAM-REM described in the Appendix (not the simplification in Figure 1). The model is based on one proposed by Malmberg and Shiffrin (2005) for free recall and modified for cued recall by Verde (2009). The simulations are qualitative: Their purpose is to illustrate how a competitor interference model can produce a range of apparently strength-independent results like those frequently reported in the RIF literature. The parameter values were chosen by taking values used by Malmberg and Shiffrin and by Verde in their simulations and making small modifications to produce rates of recall similar to those observed in the empirical data reported later. Thus, the present stimulations did not require unusual parameter values and make their point using values similar to previous applications of SAM-REM. Across the four simulations described below, all parameters were fixed save for the two responsible for the storage rates of context and item features, u^*_c and u^*_i, respectively.

The simulated experiments were identical in design to the experiments reported later. Each virtual participant studied a set 48 pairs belonging to six categories, with eight pairs per category. These were analogous to category–exemplar pairs (*FRUIT Cherry*). Each stimulus pair was represented by a vector of 20 category context and 20 item features. Item features were generated uniquely for each stimulus. Context features were generated uniquely for each category. All stimuli within a category possessed the same context features, reflecting their shared category cue. Following the standard retrieval practice design, three of the categories were practiced categories, with half of the pairs within a category designated P+ items and half of them designated P− items. Pairs from the remaining three nonpracticed categories were designated NP items. The initial study phase consisted of a single encoding trial for each item. This was followed by a practice phase. In Simulations 1–3, P+ items were given two additional encoding trials during practice. In Simulation 4, P+ items were not repeated; instead, six novel stimuli belonging to the practiced categories (analogous to extralist items) were each given a single encoding trial. Finally, all stimuli were tested with probes consisting of the category context features and the initial two item features, analogous to a category–word stem cue (*FRUIT C_?*).

Storage parameters for encoding during initial study were fixed for all stimulations at $u^*_c = .02$ and $u^*_i = .02$ to represent equal processing of context and item information. However, it is well known that people can process the same stimuli differently across situations (perhaps reflecting differences in attention, motivation, or strategy) and that these differences in processing lead to differences in the quality of encoding (Craik & Lockhart, 1972). This can be modeled by varying the storage parameters. Simulations 1–3 demonstrate the effects of strengthening, showing that differences in the processing of context and item information during the practice phase can produce different patterns of facilitation (P+ items) and suppression (P− items). These patterns will be related to real data in the next section. For the moment, the simulations can be viewed purely as a parametric test of the model.

Simulated rates of accurate recall are shown in Figure 2. Simulation 1 demonstrates the effect of an increase in category context encoding during practice ($u^*_c = .03$, $u^*_i = .02$), the result of more focused attention to or more elaborate processing of context. The result is a typical RIF effect. Practice facilitates recall of P+ items but suppresses recall of P− items relative to the NP baseline. Simulation 2 demonstrates the effect of a decrease in context encoding during practice ($u^*_c = .01$, $u^*_i = .02$) due to reduced attention or processing. Practice facilitates recall of P+ items, but this time there is no significant suppression; P− items are recalled at about the same rate as NP items. There is slightly less facilitation of P+ items because u^*_c contributes to recall of P+ items. However, the difference in P+ facilitation between Simulations 1 and 2 is parameter dependent; under some conditions, it could be quite small. Shifting attention from one aspect of a stimulus to another might result in an encoding trade-off. This is demonstrated in Simulation 3, where a decrease in context encoding is accompanied by an increase in item encoding ($u^*_c = .01$, $u^*_i = .03$). Practice facilitates recall of P+ items to the same extent as in Simulation 1 but with no suppression of P− items. In summary, the pattern in Simulation 1 resembles RIF following retrieval practice where processing the category context is emphasized, and the patterns in Simulations 2 and 3 resemble the absence of RIF following nonretrieval practice (e.g. extra study) where processing the category context is deemphasized. Simulations 1–3 show that dissociations between target recallability and competitor forgetting are possible and depend on how targets are strengthened (see Malmberg & Shiffrin, 2005, for a related account of the list-strength effect in free recall).

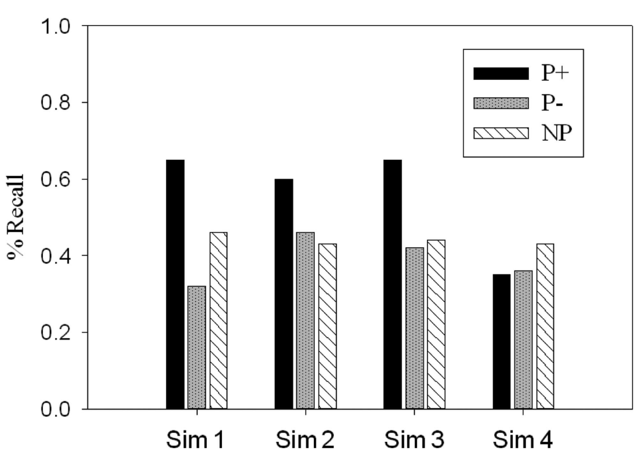

Figure 2. Simulations of the SAM-REM model. Simulations 1–3 show the effect of varying the u^* parameters during practice as follows: Sim 1 ($u^*_c = .03$, $u^*_i = .02$), Sim 2 ($u^*_c = .01$, $u^*_i = .02$), Sim 3 ($u^*_c = .01$, $u^*_i = .03$). Sim 4 shows the effect of increasing the number of competitors. P+ items were not practiced; instead, novel items were presented during practice. The u^* parameters were identical in study and practice ($u^*_c = .02$, $u^*_i = .02$). A retrieval-induced forgetting (RIF) effect is evident in Simulations 1 and 4. It is absent in Simulations 2 and 3. P+, P− = items from practiced categories; NP = items from nonpracticed categories.

Simulation 4 demonstrates the effect of varying the number of competitors. During the practice phase, P+ items are not presented. Instead, novel stimuli belonging to the same categories as P+ and P− items are studied in the same fashion as the initial study phase ($u^*_c = .02$, $u^*_i = .02$). Obviously this does not facilitate P+ items. However, encoding additional stimuli associated with the cue suppresses recall of P− items, a typical RIF effect. Note that the degree of suppression would be even larger if the novel items were encoded under the practice conditions of Simulation 1 with enhanced context encoding. Despite its significant role in forgetting, the number-dependent nature of competitor interference is rarely discussed in the RIF literature.

In the next section, the properties of competitor interference illustrated in the SAM-REM simulations are tested in a series of experiments. It is argued that both the simulations and the empirical findings require a reconsideration of several major findings in the RIF literature. The focus turns first to strength-dependent competition and a test of the differential encoding hypothesis demonstrated in Simulations 1–3. Experiments 1 and 2 replicate the often observed finding that retrieval practice leads to RIF but study practice does not. Experiments 3–5 show that the RIF effect can be made to appear and disappear under nonretrieval (study practice) conditions by manipulating the degree to which category context and item information are processed during practice. The focus then turns to number-dependent competition. There are some situations in which RIF that is attributed to inhibition might be caused instead by interference due to an increase in the number of competitors. Experiment 6 shows that studying (without retrieving) new exemplars during practice can produce a RIF effect, as demonstrated in Simulation 4.

Strength-Dependent Competition

Many studies have shown that retrieval practice suppresses recall of competitors but nonretrieval practice does not, even though both types of practice "strengthen" (i.e., facilitate recall) of the practiced item. This finding is typically interpreted as being inconsistent with the mechanism of competitor interference. As the SAM-REM simulations clearly show, such an interpretation is not quite correct. A dissociation between recallability and interference may pose a problem for simple models such as the one described by Rundus (1973). It is not a problem for more complex models. Note that the model used to illustrate this point was not constructed specifically for this purpose. SAM-REM and its parent models are general models of memory that have been applied to a wide range of phenomena in recall, recognition, and priming.

The simulations make the important point that tests of strength dependence often employed in the RIF literature do not, in theory, discriminate between mechanisms of inhibition and competitor interference. This has implications for the case for inhibition that will be explored later. A more immediate question is whether the model simulations offer not just a theoretical but a plausible account of RIF. The best way to answer this is by empirically testing the hypothesis that the form of encoding during practice mediates the emergence of a RIF effect. Before doing so, it is worth considering what the differential encoding hypothesis might have to say about previous findings.

Investigations of strength dependence in RIF have tended to use category–exemplar pairs like *FRUIT Cherry*. One can assume that the association between the category name and the exemplar is so well learned that, once the relevant categories have been established during the study phase, the focus of the task becomes learning the exemplars. If pairs are presented again during the practice phase for additional study, participants might be expected to pay little attention to the category name and focus instead on the exemplar. The category name is no longer helpful to learning (or to put it another way, little is gained by attending to the category name). On the other hand, practice involving cued recall (*FRUIT C_?*) forces people to process the category name much more deeply; it is key to producing an answer, especially if the word stem cues are not unique. With category–exemplar pairs, the possibility that people process the category context more during recall than during additional study could explain the absence of the RIF effect in the latter condition (Hulbert et al., 2012; Johansson et al., 2007; Staudigl et al., 2010; Wimber et al., 2009).

Rather than using additional study, some investigators have used a noncompetitive practice task requiring recall of the category name, not the exemplar (*FR_? Cherry*). The inhibition account predicts no RIF effect because the task does not require the activation (and suppression) of other exemplars. On the other hand, the task does require attention to the cue. If the category name is encoded as context, the competitor interference account predicts a RIF effect. The findings have been mixed, with RIF observed in some studies (Jonker & MacLeod, 2012; Raaijmakers & Jakab, 2012) but not others (Anderson, Bjork, & Bjork, 2000; Hanslmayr, Staudigl, Aslan, & Bäuml, 2010; Saunders, Fernandes, & Kosnes, 2009). These discrepancies invite speculation about possible differences in encoding during competitive (*FRUIT C_?*) and noncompetitive (*FR_? Cherry*) retrieval practice.

Consider that producing an answer to *FRUIT C_?* is difficult. In a typical design, the target *Cherry* is one among dozens of studied exemplars and previously appeared only once. Focusing on the category–exemplar association offers an efficient retrieval path to the target; doing so binds context and item information so that they are stored within a single representation, as was assumed in the SAM-REM simulations. Contrast this with the ease of producing the answer to *FR_ Cherry?* In a typical design, the target *FRUIT* is one of only a handful of category names, all of which have been repeated many times. The answer may be so readily apparent from the word stem (*FR_*) alone that there is little need to process the category–exemplar association, resulting in the category and exemplar being processed separately. Failure to bind category context and item information within a single representation would produce exemplar representations that have less contextual overlap with competitors. Interestingly, the two studies that did observe RIF following noncompetitive retrieval practice (Jonker & MacLeod, 2012; Raaijmakers & Jakab, 2012) used a slightly more difficult form of the task. Participants were asked to produce the category name given only the exemplar. The absence of a category stem cue (*FR_*) made it necessary to think about the category–exemplar association in order to produce an answer. Processing this association would lead to binding of context and item information.

The issue with the practice tasks described above is that when the cue and target have a strong preexisting association, there may be little incentive to focus on the stimulus features that cause interference unless the practice task explicitly requires that focus. When the cue–target association has to be learned during the experiment, on the other hand, people might be expected to focus on the association even during study practice. Shivde and Anderson (2001) found that with mildly associated pairs (*Arm–Missile*), retrieval and study practice produced similar RIF effects. Anderson and Bell (2001) found the same to be true with unrelated person–object pairs (*the Actor is looking at the Violin*).[4] However, Ciranni and Shimamura (1999, Experiment 5) failed to find a RIF effect following study practice using stimuli consisting of shapes with unique locations but shared colors (three colors, four shapes per color). During retrieval practice, shapes were recalled given the color and location cues. During study practice, colored shapes were shown in their locations. The final test required recalling shapes given color and location cues. A notable aspect of the design is that there were two cues, one that led to competition with other items (color) and another that did not (location). Because location was a perfectly discriminative cue, a reasonable strategy during study practice would be to focus on the location–shape association rather than the imperfectly discriminative color–shape association. Retrieval practice, on the other hand, may have often called for the supplementary use of color as a cue on trials when location did not immediately cue shape. Focus on different aspects of context (some of which would not produce interference) may explain the different effects of retrieval and study practice in Ciranni and Shimamura's study.

Applying the differential encoding hypothesis to past findings is necessarily speculative. It also does not exclude the possibility that other factors contribute to forgetting, including inhibition or other aspects of competitor interference. For example, Raaijmakers and Jakab (2012) proposed another competition-based explanation for the dissociation between P+ recallability and P− suppression. They noted that the typical absence of feedback during retrieval practice means that some P+ items are recalled and others are not. Therefore, not all P+ items benefit from practice. During study practice, on the other hand, all P+ items benefit. If retrieval is assumed to be more effective than study at strengthening, then, following retrieval practice, successfully recalled P+ items will be at high strength and nonrecalled P+ items will be at low strength. Following study practice, all P+ items will be at medium strength. Average recall of P+ items may turn out to be equivalent in the two conditions, but the high-strength P+ items in the retrieval condition may produce more interference than the more numerous medium-strength P+ items in the study condition. The potential problem created by lack of feedback is plausible and may have

[4] Anderson and Bell (2001) reported that only participants who claimed to engage in "covert retrieval" during study practice showed a significant RIF effect. In terms of differential encoding, these participants may have been the ones most likely to focus on the cue–target association.

played a role in some previous findings. It was avoided in the experiments to follow by providing feedback during retrieval practice, so that most P+ were successfully recalled.

General Method (Experiments 1–5)

Materials and Design

The critical stimuli consisted of eight exemplars from each of six semantic categories (*animals, body parts, clothing, fruits, professions, instruments*). Exemplar rank ranged from 3 to 9.1 (Van Overschelde, Rawson, & Dunlosky, 2004). No two exemplars within a category shared the same initial letter. All exemplars were presented during the study phase. For the three practiced categories, four exemplars (P− items) appeared in Block 1 of the final test. The remaining four exemplars (P+ items) appeared in the practice phase and Block 2 of the final test. P+ items were tested in the last block to ensure that any effects observed on P− items could be attributed to practice manipulations rather than to output interference from P+ items. For the three nonpracticed categories, four exemplars (NP− items) appeared in Block 1 of the final test. The remaining four exemplars (NP+ items) appeared in Block 2 of the final test. NP+ and NP− items served as the controls for P+ and P− items, respectively. In addition to the critical stimuli, a number of filler stimuli were drawn from two other categories (*countries*, *vehicles*). The assignment of categories and exemplars to conditions, and the position of items in study, practice, and test lists, were randomized uniquely for each participant.

Procedure

Participants were seated at individual computers. The experiment progressed in three phases: study, practice, and final test. At the beginning of the study phase, participants were told that they would be shown a list of category–exemplar pairs that they should try to remember. Individual pairs (*FRUIT Cherry*) were then presented on the computer screen, each for 3,000 ms followed by a 500-ms interstimulus interval (ISI). The study list consisted of 56 items (48 critical items, with four filler items at the beginning and four filler items at the end of the list as primacy/recency buffers). During the practice phase, individual items were presented for encoding in a manner unique to each experiment. Each P+ item was presented twice, once in the first half and once in the second half of the practice list. The practice list consisted of 28 items (24 critical items, with two filler items at the beginning and two filler items at the end of the list). During the final test phase, each cued recall trial began with the presentation of a retrieval cue consisting of the category name and initial letter of the target exemplar (*FRUIT C_?*). Participants were instructed to press the space bar as soon as they remembered the target and then type their answer on the keyboard. If they did not remember studying an exemplar beginning with that letter, they were instructed to not guess but instead type *no.* The retrieval cue remained onscreen until a response was made. A 2,000-ms ISI followed each response. The final test began with four filler trials followed by two 24-trial blocks. P− and NP− items were tested in Block 1. P+ and NP+ items were tested in Block 2. The two-block structure of the test list was not revealed to participants, who experienced only a continuous 52-trial test list.

Experiments 1 and 2

Many studies have shown that though retrieving P+ items during the practice phase suppresses recall of P− items, merely studying P+ items during practice does not. The purpose of Experiment 1 (retrieval practice) and Experiment 2 (study practice) was to replicate both of these findings.

Method

Participants. Fifty-five University of Plymouth undergraduates participated for course credit (Experiment 1 = 27, Experiment 2 = 28).

Materials and procedure. See General Method. The two experiments were identical in all respects save for the task used during practice.

In Experiment 1, during the practice phase P+ items were presented for cued recall. On each trial, a single retrieval cue consisting of the category name and initial two letters of the target exemplar (*FRUIT Ch_?*) was presented in the center of the screen. Participants were instructed to press the space bar as soon as they remembered the target and then type their answer on the keyboard. If they did not remember studying an exemplar beginning with those letters, they were to type *no.* The retrieval cue remained onscreen until a response was made. After every response, the correct answer (*FRUIT Cherry*) was displayed for 1,000 ms to ensure encoding of the P+ item. Trials were separated by a 2,000-ms ISI.

In Experiment 2, during the practice phase P+ items were presented for additional study. Participants were told that they would have another chance to see some of the pairs and, as before, should try to remember them for later. On each trial, a single category–exemplar pair (*FRUIT Cherry*) was shown in the center of the screen for 3,000 ms followed by a 500-ms ISI. The display procedure was identical to that used during the study phase.

Results and Discussion

Rates of accurate recall are shown in Table 1. The critical comparisons were between P− and NP− items, which appeared in the first half of the test, and between P+ and NP+ items, which appeared in the second half of the test.

Experiment 1. During retrieval practice, participants successfully recalled P+ items 90% of the time upon their second presentation. The encoding that occurred during the practice phase enhanced the memorability of the P+ items, which were recalled at a higher rate than NP+ items, $t(26) = 11.87$, $p < .001$. Enhanced recall of P+ items was accompanied by suppressed recall of P− items, which were recalled at a lower rate than NP− items, $t(26) = 2.48$, $p = .02$.

Experiment 2. The encoding that occurred during the practice phase enhanced the memorability of the P+ items, which were recalled at a higher rate than NP+ items, $t(27) = 5.73$, $p < .001$. Enhanced recall of P+ items was not accompanied by suppressed recall of P− items, which were recalled at a higher rate than NP− items, $t(27) = 2.16$, $p = .04$. The latter trend was unexpected but must be interpreted with caution, given the slightly depressed recall rate for NP− items in this experiment. Table 1 shows that recall rates of NP− items were very similar across the six exper-

Table 1
Rates of Correct Recall

Experiment	Practice task	P+ *M*	P+ *SD*	NP+ *M*	NP+ *SD*	P− *M*	P− *SD*	NP− *M*	NP− *SD*
1	Cued recall	0.72	0.17	0.30	0.16	0.32	0.14	0.41	0.19
2	Study	0.65	0.18	0.37	0.21	0.46	0.20	0.37	0.19
3	Best category	0.70	0.15	0.37	0.16	0.33	0.19	0.42	0.16
4	Feelings (context)	0.69	0.20	0.34	0.17	0.32	0.18	0.46	0.17
5	Feelings (no context)	0.58	0.18	0.40	0.18	0.42	0.17	0.44	0.13
6	Study (extralist)	0.29	0.16	0.33	0.13	0.32	0.17	0.44	0.21

Note. The retrieval-induced forgetting (RIF) effect is measured by the comparison of P− and NP− items, which were tested in the first half of the test. The facilitation of practiced items is measured by the comparison of P+ and NP+ items, which were tested in the second half of the test. In Experiment 6, P+ items were not practiced and appeared only in the study phase. P+, P− = items from practiced categories; NP+, NP− = items from nonpracticed categories.

iments, as would be expected given that NP− items were encoded under identical conditions. The rate of P− recall in Experiment 2 was similar to that of NP− items in the other experiments, consistent with a null RIF effect. The outlier is the rate of NP− recall in Experiment 2.

The findings match those of other studies using similar materials and procedures (Hulbert et al., 2012; Johansson et al., 2007; Staudigl et al., 2010; Wimber et al., 2009). Inhibition theory predicts that RIF should be retrieval dependent, occurring only when the practice task involves retrieval of P+ items. Consistent with this prediction, the RIF effect was present in Experiment 1 where practice involved recalling P+ items but was absent in Experiment 2 where practice involved additional study of P+ items. The pattern of results in Experiments 1 and 2 has been consistently interpreted in the literature as strong support for the inhibition account of RIF because it seems to be inconsistent with competitor interference.

As the SAM-REM simulations have shown, the pattern is not necessarily inconsistent with competitor interference. The differential encoding hypothesis suggests that a task like category–word stem cued recall (*FRUIT C_?*) requires a focus on the cue–target association and will lead to enhanced storage of the context features responsible for producing competitive interference. A task that requires only the study of category–exemplar pairs (*FRUIT Cherry*) does not require a focus on the cue–target association because with materials such as these, the association is already well learned. The challenge in the task is to learn the exemplars, and participants likely attend mainly to the exemplar when the pair is repeated during study practice. Encoding the features of the target item will contribute to its subsequent recall but will have little effect on the recall of other items. The differential encoding account of the dissociation between P+ recall and P− suppression observed in Experiments 1 and 2 was tested in Experiments 3–5.

Experiment 3

The ability of SAM-REM to produce the two different patterns of performance observed in Experiments 1 and 2 makes the model seem quite flexible. However, the factors that produce these different patterns have been made explicit and can be tested. The model predicts that encoding that encourages the processing of interference-relevant context should produce competitor interference. This could include retrieval practice, but it could also include various forms of study practice. For example, additional study of P+ items that actively encourages processing of the category–exemplar association should have a negative impact on the recall of P− items. The inhibition account, on the other hand, predicts a RIF effect only when the practice task involves retrieval.

Experiment 3 tested the prediction of the differential encoding hypothesis that a RIF effect will emerge during some forms of study practice. During the practice phase, each P+ category–exemplar pair was presented, and participants were asked decide whether the category was the first category they would choose for the given exemplar. For example, with the pair *VEHICLE rowboat*, if asked "what category does rowboat belong to?" participants were to consider whether they would choose VEHICLE or some other category, perhaps WOODEN THINGS. The task required semantic processing of the item in relation to the category cue, but it did not require that the item be retrieved from memory.

Method

Participants. Thirty-one University of Plymouth undergraduates participated for course credit.

Materials and procedure. See General Method. During the practice phase, P+ items were presented for category judgments. An individual pair (*FRUIT Cherry*) was shown on the computer screen for 3,000 ms, after which the question "Is this the first category you would choose for this item?" appeared below the pair. Participants were instructed to consider the target word (*Cherry*); if they were asked to choose a category for the word, would the presented category (*FRUIT*) be their first choice or would they choose a different category as their first choice? Participants responded by pressing the *1* or *2* key to indicate "yes" or "no," respectively. Trials were separated by a 2,000-ms ISI.

Results and Discussion

Rates of recall are shown in Table 1. The encoding that occurred during the practice phase enhanced the memorability of the P+ items, which were recalled at a higher rate than NP+ items, $t(30) = 11.29$, $p < .001$. Enhanced recall of P+ items was accompanied by suppressed recall of P− items, which were recalled at a lower rate than NP− items, $t(30) = 2.96$, $p = .006$. The RIF effect was similar to that observed in Experiment 1, which used retrieval practice. The results are consistent with the prediction that a focus on the processing of the local context (*FRUIT*) in relation to the target item (*Cherry*) should increase competitor interference, as shown in Simulation 1. According to the inhibition account, on the other hand, RIF should have been absent because retrieval of the target item is necessary to trigger the inhibition of competitors and the practice task did not require retrieval.

People might sometimes adopt a covert retrieval strategy even when retrieval is not explicitly required by the task (Anderson & Bell, 2001). For example, while making category judgments in the practice phase, participants may have attempted to recall prior encounters with the pairs during the study phase. Although this is unnecessary and irrelevant to the category judgments, participants may have been motivated by a desire to rehearse the exemplars in preparation for an expected memory test. If this were the case, the use of a covert retrieval strategy would seem even more likely during the study practice of Experiment 2, where the focus was explicitly to rehearse for a memory test. It is hard to explain the use of covert retrieval in Experiment 3 but not in Experiment 2. Moreover, the many failures to observe a RIF effect following study practice suggest that covert retrieval is not common (see Verde, 2009). Finally, it might be noted that the encoding instructions during practice did require the retrieval of semantic knowledge about the exemplar. However, this retrieval is noncompetitive; it might activate information about the exemplar itself, but there is no obvious reason for it to activate memories of other studied items.

Experiments 4 and 5

The intent in Experiments 4 and 5 was to manipulate the processing of context in a more controlled manner. As in Experiment 3, the practice task was one that plausibly encouraged the encoding of the category context. The task did not require retrieval of P+ items and so should not, according to the inhibition account, produce RIF. In Experiment 4, during the practice phase, each P+ category–exemplar pair was presented and participants were asked to decide how they felt about the item. Participants responded on a 7-point rating scale where 1 = *not like* and 7 = *like.* Attitudes are context dependent (Fazio, 2007), and for these judgments participants would likely use the category as a way to contextualize their feelings. For example, with the pair *VEHICLE rowboat*, participants might rate their feelings for rowboat given its properties as a vehicle.

In Experiment 5, the practice task was identical but the exemplar was presented alone without the category name. The absence of the interfering context during practice is a strong version of the condition depicted in Simulations 2 and 3. Of course, participants might sometimes spontaneously think of the categories during practice, given their recent exposure during the study phase. However, this would certainly occur far less often than in Experiment 4, where the categories were explicitly presented on every trial. The differential encoding hypothesis predicts that competitor interference should, at minimum, be greater in Experiment 4 than in Experiment 5. More likely, the RIF effect should be absent in Experiment 5 as it was with the study practice of Experiment 2.

Method

Participants. Fifty-two University of Plymouth undergraduates participated for course credit (Experiment 4 = 27, Experiment 5 = 25).

Materials and procedure. See General Method. In Experiment 4, during the practice phase P+ items were presented for feelings judgments. An individual pair (*FRUIT Cherry*) was shown on the computer screen for 3,000 ms, after which the question "How do you feel about this item?" appeared below the pair. Participants were instructed to make a subjective judgment about their feelings. Participants were given a 7-point rating scale (with the labels 1 = *not like,* 4 = *neutral,* and 7 = *like*), and they pressed a number key to indicate their feelings. Trials were separated by a 2,000-ms ISI. In Experiment 5, the practice task was identical except that each exemplar (*Cherry*) was presented by itself without the category name.

Results and Discussion

Rates of recall are shown in Table 1.

Experiment 4. The encoding that occurred during the practice phase enhanced the memorability of the P+ items, which were recalled at a higher rate than NP+ items, $t(26) = 8.41$, $p < .001$. Enhanced recall of P+ items was accompanied by suppressed recall of P− items, which were recalled at a lower rate than NP− items, $t(26) = 3.62$, $p = .001$.

Experiment 5. The encoding that occurred during the practice phase enhanced the memorability of the P+ items, which were recalled at a higher rate than NP+ items, $t(24) = 4.93$, $p < .001$. Enhanced recall of P+ items had no effect on P− items, which were recalled at the same rate as NP− items, $t(24) = 0.42$, *ns*.

In Experiment 4, a RIF effect was again observed with a practice task that did not require retrieval of the P+ items. The category name was presented alongside the exemplar during the feelings judgment. In Experiment 5, when the category name was removed and the exemplar was presented alone during the feelings judgment, the RIF effect disappeared. The presence and absence of a RIF effect tied to the presence and absence of the interfering context is consistent with the differential encoding hypothesis. Because the encoding instructions were identical in the two experiments, the results also argue against the possibility raised by Saunders et al. (2009) that any form of semantic retrieval related to the exemplar will produce RIF (see also Jonker & MacLeod, 2012). Two things might be noted about the effect of the practice task on P+ items in Experiment 5. First, there was noticeably less facilitation than in Experiment 4, where the category cues were provided during practice. This is not surprising. The cue–target association is helpful for later recall of the target, and practice that does not promote the encoding of this information will be less beneficial. Second, practice in the absence of the cue still facilitated recall relative to the NP+ baseline, consistent with the role described by SAM-REM of item information in the recovery process.

Number-Dependent Competition

Discussion in the RIF literature has focused exclusively on the strength dependence of competitor interference and has had little to say about its number dependence. This may be due to a perception that the case against strength-dependent forgetting is sufficiently strong that other aspects of competitor interference models need not be considered. However, the previous section established that a strength-dependent model offers a viable alternative to inhibition for some cases of RIF. This section will consider whether other cases of RIF previously attributed to inhibition might instead be explained in terms of number-dependent forgetting. A clear example is the use of extralist retrieval to produce RIF. A number of studies have shown that generating new exemplars of a category during the practice phase reduces the ability to recall studied exemplars (Bäuml, 2002; Storm, Bjork, & Bjork, 2007, 2008; Storm et al., 2006; Storm & Nestojko, 2010). The retrieval of novel category exemplars is thought to produce inhibition in the same way as the retrieval of studied exemplars. The claim is that attempting to retrieve from a category, regardless of what is retrieved, will activate other exemplars and lead to their inhibition.

A study by Bäuml (2002) is of particular interest because it compared extralist retrieval practice to nonretrieval practice. Participants were shown exemplars with category labels and asked to relate each exemplar to its category while rehearsing it for a memory test. During the practice phase, a new set of exemplars from the studied categories was presented. In the retrieval practice condition, participants generated the exemplars from category labels and word stems. In the study practice condition, participants were shown exemplars with category labels and had to name the exemplar. A RIF effect was observed only in the retrieval practice condition. The absence of a RIF effect in the nonretrieval practice condition is at first glance inconsistent with the number-dependent forgetting. However, in the naming task, attention to the category–exemplar association is not only unnecessary but of negative benefit, as it would slow down naming the exemplar. Failure to attend to the category context could explain the lack of RIF in this particular practice task.

This interpretation of Bäuml's (2002) results is speculative, and it is therefore useful to demonstrate number-dependent forgetting empirically. Experiment 6 was identical in most respects to Experiment 2, in which additional study of P+ items failed to produce a RIF effect. However, in place of the P+ items, a set of novel (extralist) exemplars belonging to the same categories as P+ items was studied during the practice phase. As shown in Simulation 4, increasing the number of competitors associated with the category cue can produce a RIF effect even in the absence of retrieval.

Experiment 6

Method

Participants. Twenty-nine University of Plymouth undergraduates participated for course credit.

Materials and procedure. The experiment followed the General Method but with some differences in the design of the practice phase. For each of the critical categories, an additional set of six novel exemplars was obtained for use during the practice phase. None of these shared their initial letter with studied exemplars from the category. During the practice phase, the novel exemplars from each of the practiced categories were studied (P+ items were not presented during practice). At the beginning of the phase, participants were told that they would view more pairs and, as before, should try to remember them for later. Each of the category–exemplar pairs was shown once, so that the practice list consisted of 22 items (18 critical items, with two filler items at the beginning and two filler items at the end of the list). Individual pairs (*FRUIT Apricot*) were shown on the computer screen for 3,000 ms with a 5,00-ms ISI. The display procedure was identical to that used during the study phase. The novel exemplars presented during practice were not included in the final test.

Results and Discussion

Rates of recall are shown in Table 1. Increasing the number of competitors by practicing novel items from the same category should interfere with recall of both P− and P+ items. This was clearly evident for P− items, which were recalled at a lower rate than NP− items, $t(28) = 3.02$, $p = .005$. P+ items were recalled at a slightly lower rate than NP+ items, although the difference was not statistically significant, $t(28) = 1.43$, $p = .163$. A reduction in the apparent effect on P+ items is not surprising, given that presentation of these items was delayed until the latter half of the test. By this time, other factors would have contributed to the forgetting of both P+ and NP+ items, including output interference and other nonspecific forms of interference (Verde, 2009). Thus, competition from the novel practiced items would have been responsible for a smaller proportion of the forgetting suffered by P+ items, and its effect was likely overshadowed by the other factors. The less adulterated measure of number-dependent forgetting lies with the P− items presented in the first half of the test, and the effect was clear.

Save for the materials, the study practice task used in this experiment was identical to that used in Experiment 2. The inhibition account has difficulty explaining why the RIF effect was observed here but not in Experiment 2. In competitor interference models, the strength and number of competitors contribute independently to interference. It was suggested earlier that when the cue–target relation is already well learned, as with category–exemplar pairs, people may process the cue–target association upon first encounter but are likely to give it much less attention on subsequent encounters unless the encoding task requires it. This can explain why simply presenting P+ items again for study would produce little additional strength-based interference. When novel exemplars are presented for study during the practice phase, the category context would be attended to in a manner similar to that of exemplars from the earlier study phase. The result would be an increase in the number of competitors associated with the category cue, thereby producing number-based interference. Experiment 6 demonstrates that the study of additional items causes forgetting of competitors that is not easily attributed to retrieval inhibition. The implication for studies that have used the retrieval of novel items to produce RIF is clear. Although these studies have assumed inhibition to be the source of forgetting, forgetting in fact can occur simply as a result of increasing the number of competitors associated with a cue.

Number-dependent interference may offer insight into one of the more enigmatic findings to be offered as evidence against strength-dependent forgetting. Storm et al. (2006; Storm & Nestojko, 2010) had participants study category–exemplar pairs and then asked them to generate exemplars from category–word stem cues. The word stems did not match the studied exemplars, nor could they be legally completed with any exemplar belonging to the category. This "impossible" retrieval task produced RIF, leading Storm et al. to conclude that merely attempting retrieval is sufficient to produce inhibition. The RIF effect could not have been due to the strengthening of studied items, because none were produced during practice. However, number-dependent interference offers an alternative explanation. Despite the nature of the cues, Storm et al. reported that participants often produced answers. The search for potential answers may have also brought to mind illegal examples of the category that were not verbalized. These generated items, verbalized or not, would have become associated with the category cue, increasing the number of competitors.

General Discussion

Theories of recall generally agree that the ability to retrieve a specific memory is made more difficult by the tendency for a retrieval cue to activate competing memories. However, the mechanism by which this leads to forgetting remains a matter of debate. Models based on competitor interference suggest that competition for retrieval among the associates of a cue interferes directly with the ability to recall an intended target. In contrast, Anderson et al.'s (1994; Anderson & Bjork, 1994) inhibition theory proposes that competition among associates is normally not the primary cause of forgetting. Rather, forgetting occurs because competing associates are actively inhibited to facilitate retrieval of the intended target. Inhibition theory can in principle be applied to a range of phenomena traditionally within the domain of competitor interference models, such as retroactive interference, output interference, part–set cuing, and the list-strength effect (Anderson et al., 1994). However, the most compelling support for inhibition theory has been its seemingly unique ability to account for RIF.

A primary argument against a competitor interference mechanism is the apparent strength independence of RIF. A dissociation between the facilitation of P+ items and forgetting of P− items was demonstrated in Experiments 1 and 2. Practice involving cued recall and additional study both benefited later recall of P+ items, but only recall practice suppressed recall of P− items. This replicates the pattern observed in a number of previous studies. However, subsequent experiments demonstrated that it is possible to obtain a RIF effect without retrieval practice. This was shown with three different practice tasks. With two tasks, category judgment (Experiment 3) and feelings judgment (Experiment 4), P+ items were encoded in ways meant to encourage the processing of the category–exemplar association. The SAM-REM model predicts that strengthening should exacerbate competitor interference to the extent that it involves encoding of the interfering context. Consistent with this prediction, the feelings judgment produced no RIF effect when the interfering context was absent during practice (Experiment 5). The third task simply involved additional study. It was hypothesized that with category–exemplar pairs, the association is so well learned that people attend to the category upon their first encounter with each pair but tend to ignore it thereafter. This would explain why study practice with instructions to simply "remember the items for later" produces no RIF effect (Experiment 2) unless the studied items are novel (Experiment 6). In the latter case, the SAM-REM model predicts that increasing the number of competitors should exacerbate competitor interference.

These findings are not readily explained in terms of retrieval inhibition. It has been suggested that people sometimes engage in covert retrieval even when the task does not explicitly require it (e.g., Anderson & Bell, 2001). For example, seeing the exemplar during practice might prompt participants to recall its previous appearance in the study list, triggering the inhibition of other exemplars. It is not obvious why this would be desirable in the category and feelings judgment tasks of Experiments 3 and 4. It is also not clear why participants would do this in Experiment 6 but not in Experiment 2, which used an identical practice task. The findings are entirely consistent with a competitor interference account. SAM-REM Simulations 1–3 show that a dissociation between facilitation of P+ items and forgetting of P− items is not inconsistent with strength dependence. Experiments 3 and 4 demonstrate that a RIF effect can be obtained through strengthening in the absence of retrieval. Experiments 4 and 5 demonstrate that the manner of strengthening is important: A RIF effect depends on the encoding of the interfering context.

Competitor interference suggests that forgetting is not only strength dependent but also number dependent. As shown in Simulation 4, the SAM-REM model predicts that increasing the number of competitors should exacerbate competitor interference. This prediction is consistent with the results of Experiment 6, in which the study of novel (extralist) exemplars during practice produced a RIF effect. The finding is difficult to explain in terms of retrieval inhibition. Study practice does not require retrieval and was shown in Experiment 2, as well as in previous studies, to produce no RIF effect when practice involved only items that had been studied earlier.

Conclusion

Anderson et al. (1994; Anderson & Bjork, 1994) introduced inhibition theory as an alternative to theories of forgetting based on competitor interference. Their initial studies of RIF suggested that inhibition alone could account for the findings. A sizable literature devoted to investigating RIF over the last two decades has generally supported this conclusion, in the process greatly elaborating inhibition theory and establishing it as one of the major theoretical approaches to forgetting (Anderson, 2003; Storm & Levy, 2012). The case for inhibition has relied to a great extent on its favorable comparison with competitor interference. However, recent reviews of RIF have highlighted inadequacies in the theoretical treatment of competitor interference models (Raaijmakers & Jakab, 2013; Verde, 2012).

In the RIF literature, competitor interference is discussed largely in terms of a model like the one outlined by Rundus (1973), in which an item's strength is synonymous with its recallability. This operational definition of strengthening is implicit in the notion that practice that facilitates P+ recall but has little effect on P− recall is inconsistent with strength-dependent forgetting. It is also implicit in the notion that a failure to find a correlation between P+ facilitation and the magnitude of RIF is inconsistent with strength-dependent forgetting (Hulbert et al., 2012). When strength is defined in a more nuanced way, as in the SAM-REM model, neither of these holds true. A competitor interference model of this kind offers a viable account of the RIF effect observed in the present set of experiments, and this account extends to many previous results thought to be uniquely compatible with inhibition.

RIF Reconsidered

Does inhibition offer a better account of RIF when one considers the literature as a whole? The case for inhibition has centered on four predictions thought to differentiate inhibition from competitor interference (Anderson, 2003). The inhibition account predicts that RIF should be retrieval dependent, strength independent, cue independent, and interference dependent. The first two predictions are related and were the subject of the present article. First, if RIF is a product of the retrieval process, then it will be observed only when the practice task involves retrieval. A task that does not require retrieving the target from memory, such as study practice, should not produce RIF. Second, if RIF depends only on the act of retrieval, then a task that strengthens items in the absence of retrieval, such as study practice, should not produce RIF. A model like SAM-REM can produce patterns of forgetting that are consistent with both of these predictions. Therefore, retrieval dependence and strength independence do not distinguish inhibition from competitor interference in general, although they might be useful in ruling out certain classes of models.

The ability of cue independence to differentiate inhibition from competitor interference has also been disputed. In a competitor interference model, forgetting is tied intrinsically to the retrieval cue. The cue determines via its associations which competitors are activated, and this determines the degree of interference. Inhibition acts not on the associative links but on the representation itself. An inhibited memory becomes inaccessible in any context. Therefore, RIF should be observed even when the retrieval task uses novel cues. The prediction of cue independence has been supported by a range of findings showing that RIF persists when the cue used during recall, or the retrieval task itself, differs from the cue or task used during retrieval practice. However, it is problematic for the inhibition account that cue-independent RIF is often not obtained (Jonker & MacLeod, 2012; Verde, 2012). This inconsistency has led some to argue that RIF is cue or context dependent, as predicted by competitor interference. A problem with evaluating the results from independent cue experiments is that people may sometimes reinstate earlier cues as an aid to retrieval. These cues, rather than the novel cues, may be responsible for RIF. Two types of evidence support this possibility. First, the presence or absence of RIF has been tied to thinking back to an earlier encoding episode (Camp, Pecher, & Schmidt, 2005; Perfect et al., 2004; Racsmány & Conway, 2006; Verde & Perfect, 2011). Second, cue reinstatement has been observed in recall under some conditions (Camp, Pecher, Schmidt, & Zeelenberg, 2009; Huddleston & Anderson, 2012).[5]

Of the four predictions, interference dependence seems most able to differentiate between the accounts. If the purpose of inhibition is to preempt interference from competitors, then the likelihood of an item being inhibited should depend on its potential to interfere with the retrieval target. RIF should therefore affect strong competitors but not weak competitors. With competitor interference, there is no obvious reason for this to occur. Relatively few studies have investigated interference dependence. Their results have been mixed, with some finding that strong competitors are more likely to suffer from RIF (Anderson et al., 1994; Bäuml, 1998; Storm et al., 2007) and others finding no such effect (Garcia-Bajos, Migueles, & Anderson, 2009; Jakab & Raaijmakers, 2009; Williams & Zacks, 2001). At present, the evidence does not strongly favor one account over the other.

The investigation of RIF has been motivated largely by the desire to test and develop inhibition theory, and inhibition remains the prevalent account of the phenomenon. However, as the summary above suggests, inhibition does not readily explain many findings in the literature. More important, the application of more sophisticated alternative models to RIF data is making it increasingly clear that competitor interference is difficult to rule out as a mechanism of forgetting (see also Raaijmakers & Jakab, 2012; Verde, 2009). This could be taken as an argument that competitor interference models may ultimately prove sufficient to account for RIF without the need for postulating inhibitory mechanisms. Alternatively, it could be taken as encouragement to refine inhibition theory. In framing inhibition as an alternative to competitor interference, studies of RIF have typically focused on attempting to rule out the latter as a source of forgetting. Yet, competition among the associates of a cue is fundamental to inhibition theory in that competition is what makes inhibition necessary. The tension between these two things must be resolved, and doing so is critical for continued development of the theory (Storm & Levy, 2012; Verde, 2012). A first step is to define precisely how the activation of associates creates difficulty during retrieval.

If the cost of competition is not retrieval failure, then perhaps it takes the form of slowed retrieval. Bäuml, Zellner, and Vilimek (2005) examined recall latency in the RIF paradigm from the perspective of two-stage models of recall. If search involves a sampling-with-replacement process, as in SAM-REM, free recall latency can be used as an index of interference during the sampling stage. Mean recall latency, measured from the initiation of retrieval, is known to be influenced by the number and relative strength of competitors (Wixted, Ghadisha, & Vera, 1997; Wixted & Rohrer, 1994). Bäuml et al.'s materials consisted of exemplars that belonged to a common category but one of two different subcategories (*INSTRUMENT STRING Guitar, INSTRUMENT WIND Oboe*). In Experiment 1, during the study phase, each exemplar was shown with its category and subcategory label. During the practice phase, exemplars from one of the subcategories (*Guitar*; P+ items) were recalled with the help of category–word stem cues. During the final test, each category and subcategory label was presented and participants freely recalled the items from the given subcategory. Items from the nonpracticed subcategory (*Oboe*; P−) were recalled at a lower rate than NP items, but mean recall latency of P− and NP items did not differ. Bäuml et al. concluded that inhibition from retrieval practice does not affect the sampling stage but does affect the recovery stage by decreasing the activation of P+ representations to below the threshold of recovery.

Retrieval failure at the recovery stage points to a mechanism other than competitor interference, perhaps inhibition. However, the recall latency data have to be understood in the context of a control experiment Bäuml et al. (2005, p. 1227) conducted to compare the efficacy of category and subcategory cues. The study phase was identical to the RIF experiment, but there was no practice phase. For the final test, the cues were either the category labels alone or the category and subcategory labels together. The addition of subcategory cues reduced mean recall latency, which suggests that the search set was restricted to items from the subcategory. In Bäuml et al.'s Experiment 1, subcategory cues were used in the final test. Because P+ items did not belong to the

[5] Huddleston and Anderson (2012) found evidence of spontaneous context reinstatement only when previous contexts were highly related to the test cues. They ruled out high cue relatedness in the stimulus sets from two studies using the think/no-think paradigm, but whether it is an issue in studies of RIF remains an open question.

same subcategory, they would not be expected to interfere with P− items during the sampling stage. The null effect of P+ practice on P− recall latency is therefore not inconsistent with the predictions of a competitor interference model, and it reveals little about the role played by competition in RIF.

Norman, Newman, and Detre (2007) proposed a neural network model of RIF that incorporates both competition and inhibition. The model differs conceptually from the inhibition theory described by Anderson and others. For example, inhibition leads to the permanent unlearning of associative connections, not to the temporary reduction in access often described in the RIF literature. Nevertheless, Norman et al.'s model is notable because it does make concrete its assumptions about the relation between competition and inhibition. In the model, an episodic representation consists of a pattern of associatively bound episodic and semantic units. Because a retrieval cue potentially activates a number of competing units, the system attempts to settle on a single pattern by strengthening links between units within the target representation and inhibiting links to outside units. Importantly, inhibition occurs only when competing units become activated. This can occur when retrieval cues are incomplete, as happens with retrieval practice (*FRUIT C_*). When retrieval cues are complete, as happens with study practice (*FRUIT Cherry*), there is little inhibition because nontarget units tend not to be activated. Because of this dependency between the completeness of the cue and the amount of RIF, it is unclear how the model can account for the present findings in which study and retrieval practice produced RIF effects of similar magnitude.

The works above illustrate two ways forward for inhibition theory. The first is to explore inhibition within existing models of competitor interference. Although this has been the typical approach, there is clearly a need to look beyond the simplest competition models. The second way forward is to propose new models that describe in detail how competition and inhibition work together to produce forgetting. A third possibility is to argue that competitor interference and inhibition cause forgetting under wholly separate circumstances. One could take the position, for example, that the RIF effect produced by retrieval practice is caused by inhibition, but the RIF effect produced by study practice is caused by competition. There are several objections to this position beyond its lack of parsimony. There is little precedent in the RIF literature for separating the two mechanisms in this way. On the contrary, competition is assumed to be fundamentally intertwined with inhibition. Moreover, the significance of inhibition theory has been its potential to alter our understanding of forgetting across many domains (e.g., Anderson et al., 1994). Finally, the position is untenable from the perspective of traditional views of competition, which predict competition under the same conditions that are thought to produce inhibition. To suggest otherwise would require an alternative model of competition.

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Appendix

SAM-REM Model of Cued Recall: Simulations 1–4

Recall requires matching a probe to the contents of memory in order to retrieve the specific memory that best matches the probe. The SAM-REM model proposed by Malmberg and Shiffrin (2005) takes the matching algorithm of REM (retrieving effectively from memory; Shiffrin & Steyvers, 1997) and embeds it within the retrieval framework of SAM (search of associative memory; Raaijmakers & Shiffrin, 1980, 1981). These parent models have been applied to a wide range of memory phenomena, and SAM-REM incorporates a number of theoretical principles beyond competitor interference. Readers are referred to the original sources for a wider discussion of these issues. The description below presents only the details necessary to understand the simulations.

In REM, stimuli and their corresponding memory images are represented as vectors of features with each feature assigned a value, ***V***. Feature values are drawn from a geometric distribution, emulating real-world variability:

$$P[v = v] = (1 - g)^{v-1}g, \text{ where } v - 1, \ldots \infty. \tag{A1}$$

In the present implementation, each memory vector consists of w_i features corresponding to the stimulus item and w_c features corresponding to the context in which the item is studied. These values are initially set to zero. During encoding, the feature values of the stimulus item and context are copied to the memory vector. This process is gradual and error prone, and it depends on three parameters. For each unit of time, there are t storage attempts. On each attempt, for each feature, there is probability u^* that something will be stored. The correct value is stored with probability c. An incorrect value, drawn randomly from the geometric distribution, is stored with probability 1-c. Once a value has been stored, no further storage attempts will be made for that feature.

In the simulations, a unit of time was defined as a single encoding presentation. The encoding parameters (g = .40, t = 10, and c = .80) were fixed across all simulations. Only the u^* parameter was allowed to vary. Separate values, u^*_i and u^*_c, represented the likelihood of storing information for item and context features, respectively. The values of u^*_i and u^*_c varied by simulation and are listed below. The stimuli in the simulations were analogous to category–exemplar pairs (*FRUIT Cherry*). The exemplar was defined as the item and represented by w_i features. The category name was defined as the local context and represented by w_c features. Each memory vector consisted of 40 features in all (w_i = 20, w_c = 20). Note that no provision was made to model other aspects of the temporal or environmental context. Because these features would have been the same for items being compared, their inclusion would have little effect on the patterns of recall beyond adding noise.

A recall attempt involves an initial matching stage in which the retrieval cue is compared to all of the memory images in the search set. As a standard simplifying assumption, the search set is limited to the k items previously studied in the experiment. The retrieval cue vector is compared to a given memory vector, feature by feature. The numbers of matches and mismatches, as well as the environmental base rates of features as defined by the geometric distribution, are important to calculating match. The comparison yields a likelihood ratio, λ_j, which represents the degree to which the retrieval cue matches the memory image j relative to other images:

$$\lambda_j = (1 - c)^{n_{ij}} \prod_{i=1}^{\infty} \left[\frac{c + (1-c)g(1-g)^{i-1}}{g(1-g)^{i-1}} \right]^{n_{ijm}}. \tag{A2}$$

where c defines the probability of correct storage, i is a feature value ranging from 1 to infinity, n_{ij} is the number of nonzero features in the memory image that incorrectly match the cue (regardless of value), and n_{ijm} is the number of nonzero features with value i that correctly match the cue.

The retrieval process of SAM has two stages, sampling and recovery. Memory images are sampled serially with replacement from the search set. The probability of sampling memory image j given the retrieval cue on a given sampling attempt is

$$P(j \mid cue) = \frac{\lambda^{\gamma}}{\sum \lambda_{\kappa}^{\gamma}}. \tag{A3}$$

(*Appendix continues*)

where γ is a scaling parameter (set here to $\gamma = 0.2$) that corrects for the skew of the likelihood ratio distributions (Shiffrin & Steyvers, 1998). The sampling probability depends on the degree to which the cue matches the target image relative to all other images in the search set. Interference increases as the match to nontarget images increases. When an image is sampled, the information contained in it must be recovered to a degree sufficient to support a response. The probability of successful recovery is a monotonic function of the proportion of correctly stored item features in the image,

$$P(R) = \rho^{\tau}. \tag{A4}$$

where ρ is the proportion of correctly stored features and τ is a scaling parameter (set here to $\tau = 0.4$). Sampling continues until a suitable item is recovered or the process terminates following a criterion number of sampling attempts (set here to $K_{\max} = 16$).

In each simulation, a unique set of stimuli was created for each virtual participant ($n = 300$). There were six categories. All stimuli within a category possessed the same context features but had unique item features. Eight stimuli per category were presented once for encoding during the study phase ($u^*_c = .02$, $u^*_i = .02$). In Simulations 1–3, half of the stimuli from three categories (P+ items) were presented again twice for encoding during the practice phase, allowing additional attempts to store features into their memory images (Sim1: $u^*_c = .03$, $u^*_i = .02$; Sim2: $u^*_c = .01$, $u^*_i = .02$; Sim3: $u^*_c = .01$, $u^*_i = .03$). In Simulation 4, no studied stimuli were presented; instead, a new set of six stimuli from three studied categories was presented once for encoding ($u^*_c = .02$, $u^*_i = .02$). In all the simulations, a test phased followed the study and practice phases in which each stimuli from the study phase was tested with a probe consisting of 20 context features and two item features (the latter representing the exemplar word stem). Performance in Figure 2 represents the likelihood of sampling and recovering the target of a probe. Testing order was not modeled; this level of complexity, which may include factors such as contextual drift, output interference, and specific and general interference (e.g., Verde, 2009), is beyond the scope of the present study.

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