ABSTRACT

Title of Document:	Learning to Forget: An Interference Theory of Cue-Independent Forgetting
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Memory suppression is investigated in inhibition paradigms that produce cue-independent forgetting. Because the forgotten items are not retrieved even when tested with an independent, semantically related cue, it has been assumed that this forgetting is due to an inhibition process. However, this conclusion is based on comparing inhibition to classic interference theory with a single stage of recall. Yet, memory models, which produce forgetting through a process of interference, include both a sampling and a recovery stage of recall. A neo-classic interference theory is proposed, which assumes that interference exists during recovery as well as sampling and can explain cue-independent forgetting. Three behavioral studies tested predictions of the neo-classic interference theory. Experiment 1 found support for recovery interference in testing key predictions of the theory within the think/no-think paradigm. Most importantly, learning to quickly press enter produced as much cue-independent forgetting as no-think instructions. Experiment 2 tested the role of word frequency in terms of sampling and recovery, but failed to obtain cue-independent forgetting. Experiment 3 reversed the order of blocks and produced original cue forgetting following retrieval practice with independent cues, which provided a clear manipulation of recovery strength. Lastly, a mathematical model (SAM-RI) of neo-classic interference theory was specified that captures data from Experiment 1, Experiment 3, and is extended to the greater retrieval induced forgetting.

Learning to Forget: An Interference Theory of Cue-Independent Forgetting

By

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Lastly, I am humbled to be a part of God's plan and am thankful that He has lead, provided, and loved me throughout my life and through this journey. I hope this work and my life may glorify God. His grace continually astounds and inspires me to be the best He has created me to be.

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Chapter 1: Introduction

Forgetting is usually thought of with negative connotations. This is certainly true for instances such as forgetting a spouse's birthday, a crucial ingredient at the marketplace, or what prescriptions your grandmother is currently taking. All of this could yield unfortunate outcomes. Yet for memories of a particular embarrassment or trauma, forgetting may seem to be beneficial or desirable. Freud (1966) proposed that people are able to willfully forget undesirable memories through a process he called repression, whereby memories are moved from the conscious to the subconscious. According to Freud, these repressed memories remain in the subconscious until they are "recovered," usually through therapy. Freud's proposal, which amounts to a theory of both how people forget and how they subsequently recover previously forgotten memories, has been a topic of both theoretical and applied interest. From a memory-theoretic perspective, understanding forgetting and recovery is part and parcel of understanding the basic properties of the brain. However, from an applied perspective, the validity of Freud's theory has considerable import for how people cope with unwanted memories and for the justice system (*Isley v. Capuchin Province,* 1995; Loftus, 1993; *State v. Hungerford,* 1997).

While the construct of repression has a long history in the public's lay epistemology of psychology, little rigorous scientific research has investigated how a process akin to repression might be implemented within the neurocognitive architecture. However, recent work by Anderson and Green (2001) offer some insights. They developed an inhibition theory of forgetting where repressed memories are assumed to result from a process referred to as inhibition. According to Anderson and Green, people deploy executive working memory resources to inhibit unwanted memories, which in turn prevents targeted declarative memories from entering consciousness (Anderson, 2005, 2006; Anderson & Green, 2001). If subsequent retrieval of the previously inhibited memory becomes desirable, there is a consequent deficit due to the previous inhibition. This forgetting is essentially due to deactivation of existing memories. While the inhibition theory of forgetting has led to many insights into the functioning of memory and the processes of forgetting, there are alternative mechanisms by which forgetting might take place.

The purpose of this paper is to test an alternate theory of forgetting based on the construct of memory interference. According to classic interference theory, forgetting is due to *competition* between multiple memories associated with a specific retrieval cue, as opposed to a decrease in the activation of the memory. In what follows, I provide a more detailed description of active inhibition theory and then propose a neo-classic interference theory. Three experiments are then described, which are designed to test the proposed neo-classic interference theory. My presentation of the neo-classic interference theory and experiment 1, as well as some elements of the modeling and discussion sections, are based on work to be published in the Proceedings of the National Academy of Science (Tomlinson, Huber, Reith, & Davelaar, *in press*).

Inhibition Theory of Forgetting

The only neurocognitive theory of repression involves inhibition and claims that forgetting memories occurs through active memory inhibition, which is assumed to be analogous to motor response override (Anderson & Green, 2001). In the same manner that one can supposedly stop a motor action from reaching completion once the action is initiated, one can stop a memory from reaching consciousness. In a typical motor response override situation, a person tries to overcome a strong prepotent response in order to output a weaker response that may be more appropriate or desirable for the current situation. For example, if a person knocks over a small cactus plant, their first reaction (the prepotent response) might be to reach out their hand to catch the falling object, but the person stops the completion of the action (catching the plant) before they become riddled with cacti needles (Anderson, 2006). In this example the weaker response of "not catching the plant" was appropriate, but in order to complete that action, the strong prepotent response of "catch falling object" must be inhibited. Analogously, people may engage in an inhibitory control process whereby a prepotent memory (e.g., a memory of an undesirable event) is prevented from being brought into awareness (Anderson & Green, 2001). This inhibition of the memory leads to a subsequent recall deficit for the memory, regardless of how one is probed for the memory (Anderson & Green, 2001).

Classic Interference Theory of Forgetting

Inhibition theory stands in contrast to traditional theories of forgetting based on interference at storage or retrieval (e.g. Waugh, & Norman, 1965; Raaijmakers &

Shiffrin 1981; Hintzman, 1988; Murdock, 1983). Classic interference theories posit that the inability to retrieve a target memory is caused by other memories competing for access with the target memory. Generally, there are two forms of interference: the interference from previously learned items in memory (proactive interference) or subsequently learned items (retroactive interference). For example, proactive interference might occur if you switched phone services and found it difficult to retrieve your new number. One potential explanation for this difficulty might be that your old number more readily sprang to mind, and blocked access to your new number. Conversely, retroactive interference might be found if upon adequate memorization of your new number, you found that you could no longer retrieve your old number. In this case, the new number is blocking access to the older number.

Interference based theories of forgetting explain a wide range of phenomena, such as release from proactive interference (Loess, 1968), list-length effects (Raaijmakers & Shiffrin, 1980), part-set cueing effects (Raaijmakers & Shiffrin, 1981), list-strength effects (Murdock & Kahana, 1993; Shiffrin, Ratcliff & Clark, 1990), and false memory effects (Kimball, Smith, & Kahana, 2007). Given the success of traditional interference theories of forgetting, it would be beneficial to examine an interference-based explanation of forgetting memories before adopting novel accounts of forgetting – such as inhibition theory.

Cue-Independent Forgetting

Inhibition theory has gained prominence in the field of psychology. This is largely due to the inability of classic interference theory to account for cue-independent forgetting. Cue-independent forgetting refers to recall impairment that is observed with multiple cues, including cues not initially learned with the target memory. To illustrate, consider the think/no-think (TNT) paradigm where there are four experimental phases: (1) cue-target word pair learning to establish prepotent responses; (2) suppression training for a subset of the learned memories; (3) cued recall for all items with the originally learned cues (original cues); and (4) cued recall with semantically related cues that have not been seen previously in the experiment (independent cues) (see Figure 1). For example, a participant might learn to recall the target memory "doctor" when they see the cue word "plane". This association would be built up in phase 1. In phase 2 (suppression training), they are instructed that they should not let "doctor" enter their conscious thought when presented with "plane." Following suppression training, participants are given a cued recall task where the original cue (e.g., "plane") from the initial learning is presented (i.e, original cue recall). Participants are encouraged to recall *all* of the original target words, including those words that underwent suppression training (phase 3). This task typically reveals a decreased probability of being able to recall the original target (e.g., "doctor"), relative to recall for words that did not undergo suppression training (i.e., baseline words).

The impairment in original cue recall is compatible with both inhibition and classic interference theories (see Figure 2). Within inhibition theory the recall impairment is a result of memory deactivation, whereas classic interference theory predicts recall impairment via response competition. For instance, if people learn to associate the cue "plane" with some other retrieved response (shown by the dashed line), such as sitting quietly for 4 seconds, this will serve as a competitor to the original memory (“doctor”). This response competition would lead to impaired recall. Accordingly, both classic interference and inhibition theory are able to adequately explain the original cue recall results.

However, classic interference theory and inhibition theory differ in their ability to account for independent cue recall (phase 4). For example, the word “nurse” could be used as an independent cue to retrieve the target word “doctor”. Note that any memories created during suppression training should not compete with Nurse, since Nurse was not presented during training. Therefore, any impairment found in independent cue recall would simultaneously be evidence for inhibition theory and against classic interference theory. Impaired independent cue recall has been observed with the think/no-think paradigm, providing an argument against classic interference theory.

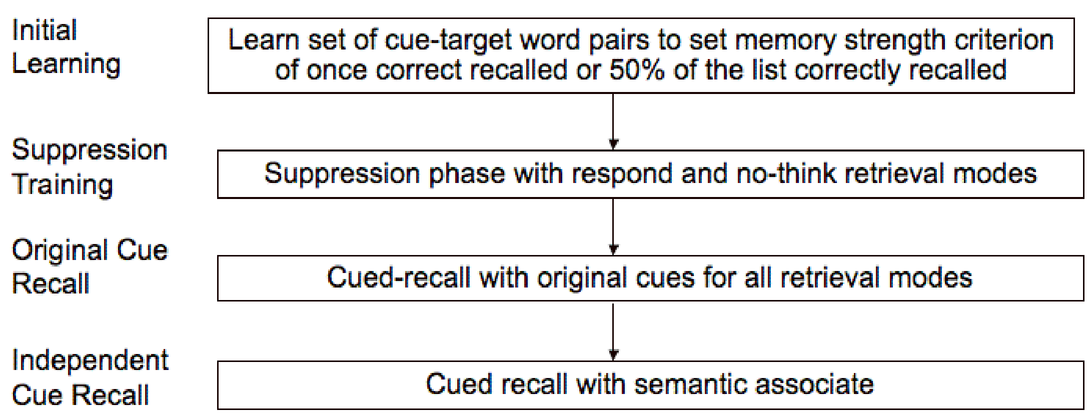

Figure 1. Think/No-Think paradigm from Anderson and Green (2001)

Cue-independent forgetting is also observed in the retrieval induced forgetting (RIF) paradigm (Anderson, Bjork, & Bjork, 2000; Anderson & Spellman, 1995). In this paradigm, the process of practicing cued retrieval of some items paradoxically causes forgetting of other items. The practiced items have a greater probability of subsequent recall, but other items that are associated with the practiced retrieval cue are more likely to be forgotten (Anderson, Bjork, & Bjork, 200; Anderson, Bjork, & Bjork, 1994; Anderson & Spellman, 1995). In the typical retrieval induced forgetting (RIF) experiment, there are four phases similar to the think/no-think paradigm: (1) initial cue-target learning; (2) selective retrieval practice; (3) original cue recall and; (4) independent cue recall. In the learning phase (1) participants are presented with cue-target word pairs. However, rather than using unrelated cue-target word pairs, the RIF paradigm uses category names as cues (i.e., fruit – orange and fruit –tangerine). Following initial learning, half of the studied categories are designated as practiced categories and the other half non-practiced categories. Within the practiced categories participants have retrieval practice with half of the learned target words (i.e., 'fruit – or__'). This retrieval practice is followed by original cue recall (phase 3), in which the participants are presented with category cues and asked to recall all the learned targets for the cue (i.e., 'fruit – '). Independent cue recall (phase 4) follows and also uses a category cue that is related to multiple studied targets (i.e., 'red – ').

The selective retrieval practice leads to improved recall for the practiced category items and impaired recall for the non-practiced category items as compared to a baseline category condition where no targets receive retrieval practice (Anderson, Bjork, & Bjork, 1994; Anderson & Spellman, 1995). For example, imagine that one learned "fruit-orange" and "fruit-tangerine", and then selectively retrieved "fruit-orange". In this case, orange would be more likely to be recalled, and tangerine less likely, compared to baseline words that received no such retrieval practice, such as "vegetable-radish".

Inhibition theory predicts decreased recall due to inhibition of the non-practiced words when practiced words are recalled. Classic interference theory predicts decreased recall for non-practiced items due to the practiced items being stronger competitors for recall. Because classic interference theory predicts recall impairment based on the practiced items being stronger competitors with the original cue, it also must predict no interference when an independent cue is presented where the targets area all equivalent competitors.

Several experiments have found recall impairment with the independent cue task in both the think/no-think and retrieval induced forgetting paradigms (Anderson & Bell, 2001; Anderson & Green, 2001; Anderson & Spellman, 1995; Johnson & Anderson, 2004; although for discussion about replication failures see Bulevich, Roediger, Balota, & Butler, 2006). This impairment holds even when participants are offered incentives for accurate recall and when given instructions emphasizing the need to recall the target words (Anderson & Green, 2001). The continued failure to recall with an independent cue indicates that this is a result of memory impairment rather than a demand characteristic.

However, whether independent cue recall is a unique marker of memory inhibition is debatable. I propose that dismissing interference theory as an explanation of cue independent forgetting is premature: Many of the findings taken as evidence for inhibition theory can be interpreted within the context of interference.

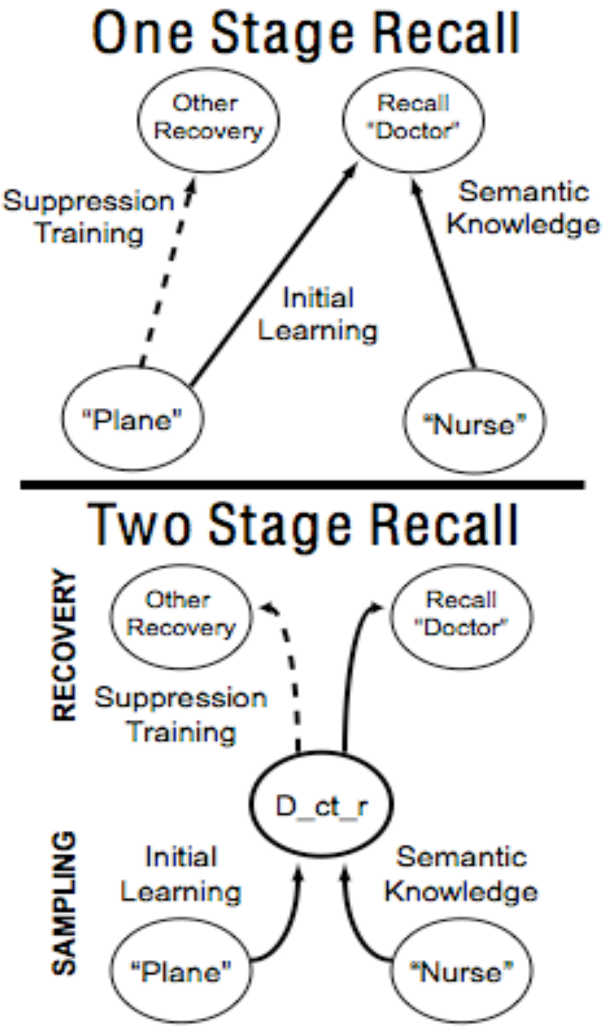

Figure 2. One stage (top panel) versus two stage (bottom panel) models or cued recall. For both models, the initially learned association between "Plane" and "Doctor" is represented by solid lines. The dashed lines between "Plane" and "Other Recovery" represents the newly learned association during suppression training, such as in the no-think and press-enter conditions.

A Neo-Classic Interference Theory of Forgetting

Classic interference theory assumes a one-stage recall process, in which the target memory is retrieved directly via the association between the cue and target. One-stage recall models only address the direct association between a cue and the target memory, and cannot explain cue-independent forgetting (i.e., plane – doctor, see top panel of Figure 2). However, most contemporary models of memory, including many global memory models, assume a two-stage recall process in which items are first sampled from long-term memory and then go through a recovery process. Although most two-stage models assume that interference occurs only during the sampling stage, I propose a novel model in which interference can operate at both stages.

In two-stage recall a partial memory trace is sampled from long-term memory (LTM). Then, this partial trace is resolved, or recovered, into a complete trace. Within this framework, sampling is a stochastic process, and all items in memory are open to the sampling process. Sampling occurs by utilizing information stored with the memory trace during encoding (associated cues and general context). After a partial memory has been sampled the recovery process is necessary in order for the system to resolve the items identity. For example, if one samples a partial memory of “d_ct_r” (see bottom panel of Figure 2), a recovery process is needed to produce “doctor”. The presence of interference during the sampling stage has hitherto been sufficient to explain most memory effects (Murdock & Kahana, 1993; Raaijmakers & Shiffrin, 1980; Shiffrin, Ratcliff & Clark, 1990). The second “recovery” process was added in order to explain the word frequency effect, where low-frequency words are more difficult to recall than high-frequency words (Deese, 1960; Hall, 1954; Sumbly, 1963). Though interference during the recovery process has never been specified in global memory models, it is a natural extension that is similar to interference in sampling.

As an example of how neo-classic interference theory accounts for recall impairment from the think/no-think paradigm consider the following example. Assume that a participant initially learns to associate “doctor” with “plane” (phase 1), and later is told to not think of “doctor” when prompted with the “plane” (phase 2). Participants may sometimes sample the partial memory trace (“d_ct_r”) in response to the previously learned cue (“plane”) during suppression training, but then learn to recover this partial memory to an alternative recovery such as “do nothing.” This alternative recovery will then provide competition with the original recovery (“doctor”) in response to any cue that results in the memory being sampled. This competition leads to impaired recall. The neo-classic interference model of recall can fully capture the independent cue recall results that have previously been touted as uniquely characteristic of inhibition theory.

The reported experiments test predictions of the neo-classic interference account. Experiment 1 tests three predictions of the neo-classic interference theory in the think/no-think paradigm. Experiment 2 employs the same paradigm from Experiment 1 while also testing the assumption from global memory models the recovery stage is critical in explaining why low-frequency words are more difficult to recall (Deese, 1960; Hall, 1954; Sumbly, 1963). Experiment 3 seeks to assess whether participants are learning an alternative recovery in a novel paradigm that extends the proposed neo-classic interference theory beyond the think/no-think paradigm. Finally, I outline a computational model of the neo-classic interference theory, which is specified with Search of Associated Memory (Raaijmakers & Shiffrin, 1981).

Chapter 2: Experiment 1

Introduction

To assess the viability of the neo-classic interference theory, three predictions of this theory were tested. First, learning *any* alternative recovery will provide interference and subsequent impaired recall. Inhibition instructions lead to impaired recall is because people are being instructed to learn an alternate recovery (i.e., do nothing) rather than the previously learned recovery (i.e., type "doctor"). Experiment 1 tests this prediction by including a press-enter task in the suppression training phase of the think/no-think (TNT) paradigm to compare with the traditional no-think instructions (see Figure 3). For the press-enter task the participants were told to press the enter key as quickly as possible in response to particular cues during suppression trials. Importantly, no instructions were provided encouraging participants to engage in inhibition.

Additionally, the neo-classic interference theory predicts that participants will show no interference effects when they are tested via recognition. The target memory is assumed to be difficult to recall due to competition at recovery during *recall*. In recognition testing, the participant does not need to engage in the recovery process as the target item is fully recovered. Therefore, neo-classic interference theory predicts diverging results for recall and recognition. Items that receive no-think or press-enter instructions should show impaired recall but not impaired recognition compared to baseline items. A recognition test was included in Experiment 1 to assess if participants show commensurate recall and recognition impairment (see Figure 3).

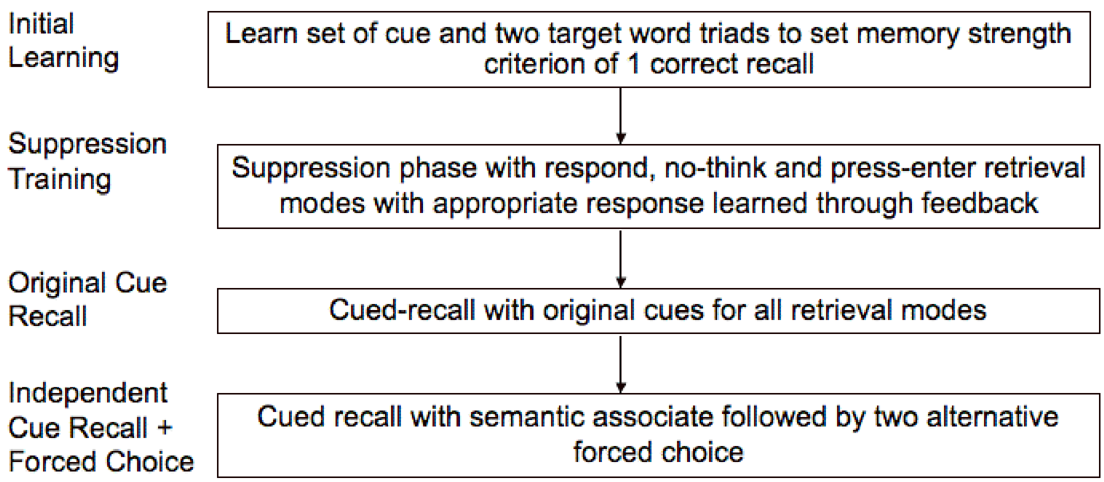

Figure 3. Modified think/no-think paradigm (Anderson & Green, 2001) used in Experiment 2

Lastly, the neo-classic interference theory predicts that memories that are more strongly learned should be less affected by interference. 'Stronger' memories should have a strong recovery strength that is a more efficient competitor for any newly learned recoveries. This was assessed in Experiment 1 by manipulating the initial learning criterion to either one or three correct recall trials (see Figure 3).

Participants

Eighty-four undergraduate students from the University of Maryland (N=54) and University of California (N=30) participated for class extra credit.

Materials

Independent cue and target words were selected from the University of South Florida (USF) Free Association Norms database (Nelson, McEvoy, & Schreiber, 1998). Forty independent cue words were selected with two associates per cue. One associate was assigned as the target item and the other was used as the distractor in the forced choice phase. For each participant the assignment of associates as target or distractor was random, as was assignment of words to conditions. The two associate words had a minimum backwards association strength (target to cue) of .01 and a minimum forward association strength (target to distractor) of .15. The two forward association strengths did not differ by more than .25. The associates were cross-referenced with the MRC Psycholinguistic Database (Coltheart, 1981) to exclude those that were not 4 to 6 letters long, at most 2 syllables, or did not have a minimum written frequency of 20 (Kucera & Francis, 1967). Emotive associates and associates that were elicited by two different meanings of the cue word were eliminated. Forty additional words were randomly assigned as cues words in the cue-target pairs used during initial learning. These were nouns of 3 to 8 letters, at most 3 syllables and did not associate to any target/distractor/independent-cue words.

Design and Procedure

This was a within subjects 2 (initial memory strength: strong or weak) x 4 (suppression learning task type: recall, no-think, press-enter, or baseline) design. The study was run entirely by computer.

There were four phases to the experiment: initial learning, suppression training, original-cue recall, and independent-cue recall interleaved with forced-choice recognition. The initial learning phase presented participants with the forty cue-target word pairs at a rate of 5 seconds per pair in an order randomly determined for each participant. Next, participants performed cued-recall testing to assess the degree of initial learning. Participants were tested with each cue word and were informed whether their typed response was correct. If incorrect, they were informed of the appropriate response to allow further learning. This test list was repeated in random order as cue words were progressively eliminated from the test list in accordance with the memory strength manipulation: for the weak memory items, cues were eliminated after the participant correctly recalled the target word once; for the strong memory items, cues were removed after three correct recalls.

The second phase was suppression training, where ten of the forty word pairs were randomly assigned to each of the four task types: recall, no-think, press-enter or baseline. Suppression training consisted of nineteen blocked repetitions of the thirty cues assigned to the no-think, press-enter, and recall conditions, with a break after the tenth block. Within each block, the thirty cues were permutated. Participants learned appropriate recall, no-think, and press-enter responses through trial-by-trial feedback. For recall cues, participants attempted to type in the appropriate target word when given the cue. Feedback for the recall task was the same as in the initial learning. The no-think cues required participants to not press any key for the 4 seconds that the cue remained on the screen. Participants were informed that they were correct following four seconds of keyboard inactivity and were informed that they were incorrect if they pressed any key. The press-enter cues required participants to press the enter key within 1.5 seconds after the cue appeared on the screen and feedback was provided to regarding this time constraint. Additionally, participants saw a score box that contained their "score" of how well they were doing, with points added or subtracted for each correct or incorrect response respectively. The points were allocated such that accuracy on recall cues resulted in more points than correct behaviors for the no-think or press-enter cues.

The third phase was a surprise cued-recall test that presented all forty of the cue words from initial learning. Cues were presented one at a time in random order and the participants were asked to recall the corresponding target words. It was stressed that accuracy was highly desirable, regardless of any previous instructions. In order to reduce additional learning during testing, no feedback was provided for this, or any of the other final tests.

The final phase was the independent cue recall and forced choice recognition, which occurred in an interleaved fashion. On each trial, the participant was presented with a previously unseen cue word that was semantically associated to one of the previously studied target words. Participants were told to use this cue to retrieve a previously studied word. Next, regardless of recall accuracy, participants saw the correct target and a distractor word that was also an associate of the cue and were told to choose the word that was previously studied. The left/right screen position of the choices was randomized. In this manner, each of the forty original target words was tested both with independent cueing and with forced choice recognition. During the independent cue recall, if the participant could not think of a word from the experiment related to the presented associate word, they were instructed to guess.

Results and Discussion

A 2 (memory strength) x 4 (task type) ANOVA was conducted for each final memory test (original cue, independent cue, and forced choice) followed by comparison tests. Reported effect size (ES) values are partial eta-squared for F-tests and Cohen's d for t-tests.

Original Cue Recall

Neo-classic interference theory predicts that there should be a main effect of memory strength on original cue recall. Strong memories may be more resistant to interference as they have stronger sampling and recovery strengths and are thus more efficient competitors for *any* interference. This was confirmed as a main effect of memory strength on recall accuracy was statistically significant, $F(1, 83) = 91.82$, $p < 0.001$, ES = 0.52. The first and fourth rows of Table 1, as well as Figure 4, show that weak memories are recalled less often than strong memories.

Similarly, as predicted by the neo-classic interference theory, a main effect of task type on recall accuracy was observed, $F(3, 254) = 60.17$, $p < 0.001$, ES = 0.42. Specifically, the neo-classic interference theory predicts that no-think and press-enter instructions should lead to similar recall performance: There should be no difference between the press-enter and no-think conditions and these conditions should have impaired recall relative to baseline and recall conditions. A conventional dependent t-test failed to reach significance, indicating no difference. While this test suggests that the two groups did not differ, traditional null-hypothesis statistical testing may be ill suited for evaluating the truth of the null hypothesis (Rouder et al., 2009). Rouder et al. (2009) proposed a Bayesian t-test, which enables one to test the whether the null hypothesis is true. Using this Bayesian approach, the Bayesian t-test yielded a value of 10.19, which can be interpreted as the null hypothesis being 10 times more likely than the alternative hypothesis[1]. In interpreting the Bayesina analysis, a factor above 3 is recommended by Jeffreys (1961) as being "some evidence" for the null, with a factor greater than 10 be considered "strong" evidence for the null hypothesis. Thus, a factor of 10.19 may be considered strong evidence for the null hypothesis. Because the no-think and press-enter tasks do not appear to differ significantly, with either in NHST or Bayes t-test criterion, these were collapsed for subsequent analyses.

Further, the neo-classic theory predicts that the no-think and press-enter items will suffer recall impairment due to learning new recoveries during suppression training (i.e., do nothing or press-enter). This recall impairment should be observed relative to other items that did not learn alternate recoveries (i.e., baseline items) and items that received continual practice with one 'correct' recovery (i.e., recall items). This was confirmed with paired sample t-tests showing that performance in the no-think and press-enter conditions was significantly lower than both the baseline, $t(83) = 4.01$, $p < 0.001$, ES = 0.44, and recall conditions, $t(83) = 13.12$, $p < 0.001$, ES = 1.43. Thus, original cue recall impairment was observed even when inhibition instructions were not present in the press-enter condition.

Lastly, there was a main effect of task type on recall accuracy for both weak, $F(3, 277) = 56.9$, $p < 0.001$, ES = 0.38, and strong memories, $F(3, 278) = 14.77$, $p < 0.001$, ES = 0.14. Neo-classic interference theory expects that weak memories should demonstrate a greater rate of recall impairment than strong memories, as weak

[1] The reported Bayes t-test used the JZS prior to keep the prior for the alternative and null similarly weighted (see Rouder et al., 2009 for a discussion of the JZS prior).

memories should suffer from interference more. To assess whether the weak memories had greater recall impairment relative to strong memories, the difference between the baseline condition versus the combined press-enter and no-think conditions was used to measure forgetting. A comparison of this difference for weak and strong memories revealed greater forgetting for weak memories, $t(83) = 2.60$, $p < 0.01$, ES = 0.28 (see Figure 4).

Retrieval Type	Recall	No-Think	Press Enter	Baseline
	Strong Memory Strength			
Original Cue recall	.96 (.02)	.83 (.02)	.82 (.02)	.86 (.02)
Independent Cue	.49 (.02)	.48 (.02)	.45 (.02)	.50 (.02)
Forced Choice Recognition	.96 (.01)	.95 (.01)	.96 (.01)	.94 (.01)
	Weak Memory Strength			
Original Cue recall	.95 (.02)	.60 (.02)	.62 (.02)	.73 (.02)
Independent Cue	.50 (.02)	.44 (.02)	.49 (.02)	.54 (.02)
Forced Choice Recognition	.96 (.01)	.92 (.01)	.93 (.01)	.94 (.01)

Table 1. Experiment 1 mean accuracy by task, condition and memory strength with observed standard errors in parenthesis

Independent Cue Recall

Neo-classic interference theory predicts a main effect of memory strength for independent cue recall. Strong memories should have greater recovery strength's than weak memories. This stronger recovery strength should enable stronger memories to be better competitors for any alternate recoveries learned during suppression training. However, there was no main effect for memory strength, $F(1, 84) = .608$, $p = .438$, as can be seen in rows 2 and five of Table 1. This may indicate that three retrievals was not sufficient to insulate recovery interference effects as one (weak memories) and three (strong memories) retrieval practices appear no different in their recall accuracy. The additional two retrieval practice may be beneficial for recall due to the combined effect of sampling and recovery, as evidenced by the main effect of memory strength for original, but not independent cue recall.

Second, as predicted by the neo-classic interference theory, a main effect of task type on recall accuracy was observed, $F(3, 254) = 2.64$, $p \leq 0.05$, ES = 0.03 (see Table 1)[2]. Specifically, the neo-classic interference theory predicts that no-think and press-enter instructions should lead to similar recall performance: There should be no difference between the press-enter and no-think conditions and these conditions should have impaired recall relative to baseline and recall conditions. A dependent t-test revealed no significant differences between these two tasks and the Bayesian t-test in favor of the null hypothesis was 6.31, indicating some evidence for the null as it is 6.31 times more likely than the alternative hypothesis. Because the no-think and press-enter tasks do not appear to differ significantly, with either in NHST or Bayes t-test, these were collapsed for subsequent analyses.

Lastly, the neo-classic theory predicts that the no-think and press-enter items will suffer recall impairment due to learning new recoveries during suppression training. This recall impairment should be relative to both baseline and recall conditions. This was mostly confirmed with paired sample t-tests showing that the no-think and press-enter conditions were significantly lower than the baseline condition, $t(83) = 2.70$, $p < 0.01$, ES = 0.29, and marginally lower than the recall condition, $t(83) = 1.52$, $p = 0.07$, ES = 0.17.

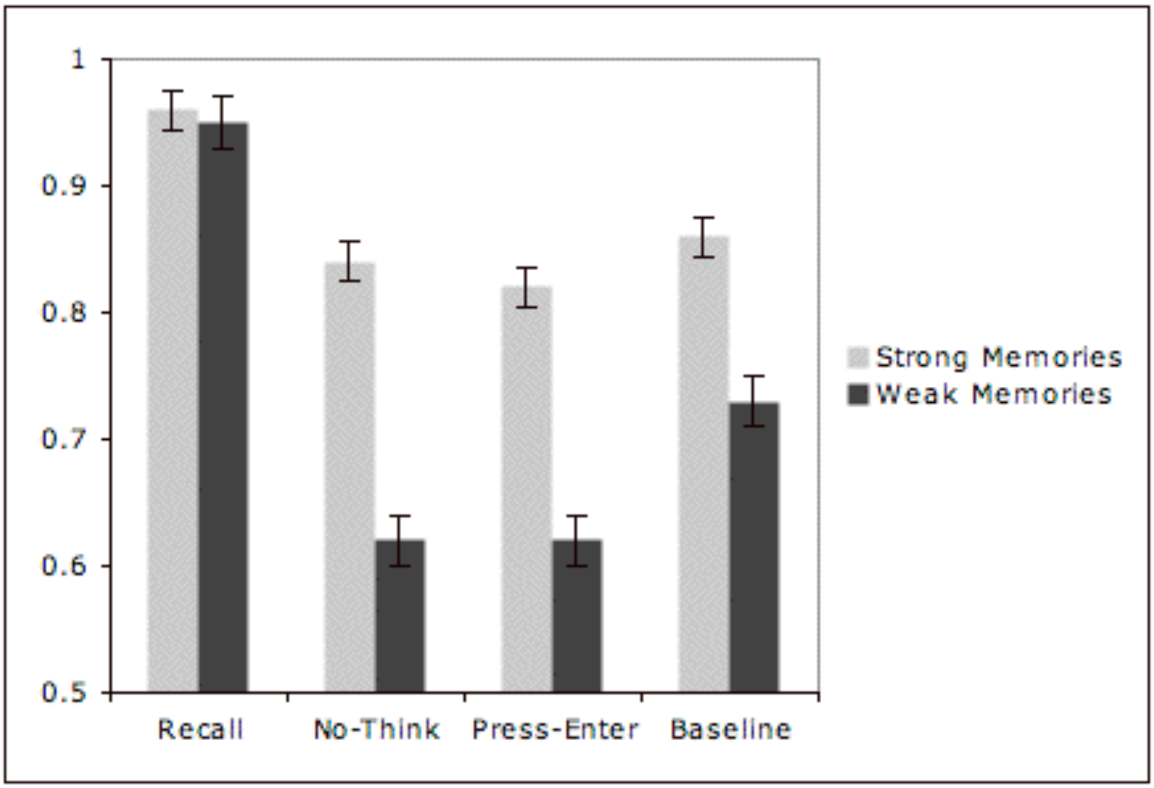

Figure 4. Experiment 1 mean accuracy of original-cue recall for the four word tasks by memory strength.

Forced Choice Recognition

Neo-classic interference theory predicts that there should be a main effect of memory strength on recognition. Strong memories should have greater self-sampling strengths, due to the increased learning, which should lead to increased recognition accuracy. This was confirmed as there was a main effect of memory strength on recognition accuracy, $F(1, 84) = 4.37$, $p < 0.05$, ES = 0.05. The third and sixth rows of Table 1 show that strong memories are recognized more often than weak memories.

Similarly, as predicted by the neo-classic interference theory, a main effect of task type on recognition accuracy was observed $F(3, 254) = 2.98$, $p < 0.05$, ES = 0.03. Specifically, the neo-classic interference theory predicts that no-think and press-enter instructions should lead to similar recognition performance. A dependent t-test revealed no significant differences between these two tasks and the Bayes t-test in favor of the null hypothesis was 7.54, indicating some evidence that the null is true as it is 7.54 times more likely than the alternative hypothesis. Because the no-think and press-enter tasks do not appear to differ significantly, with either in NHST or Bayes t-test criterion, these were collapsed for subsequent analyses.

Lastly, the neo-classic theory predicts that the no-think and press-enter items will suffer no recognition impairment due to the item being fully recovered and bypassing the recovery interference learned during suppression training. Therefore, the interference theory predicts that no-think and press-enter tasks should be no different from baseline recognition. NHST paired samples t-test revealed no difference between these groups, and the Bayes t-test was 9.02 indicating some evidence that the null hypothesis is true as it is 9.02 more likely than the alternative hypothesis. Conversely, the recall condition should be, and is, greater than the no-think and press-enter conditions due to increased self-sampling as a result of continued practice, $t(83) = 2.22$, $p < 0.05$, ES = 0.24.

As seen in Table 1, it might appear that there are ceiling effects, but if there was a ceiling effect, it clearly did not eliminate all effects. Because it was possible to observe significant improvements in the recall condition (i.e., in the direction of ceiling), then it should have been possible to observe deficits in the suppression conditions (i.e., in the direction of floor).

In sum, Experiment 1 confirmed three qualitative predictions derived from the neo-classic interference theory: learning *any* alternate recovery (such as pressing enter) results in cue-independent impaired recall, recognition performance showed no impairment for suppressed items (i.e., no-think and press-enter conditions) and items that are learned to a higher criterion show less effects of interference at recall.

Chapter 3: Experiment 2

Introduction

Experiment 1 provided support for the neo-classic interference theory of forgetting. Experiment 2 sought to replicate the results of Experiment 1 as well as test a prediction from interference theory that is more intimately tied with the recovery stage. Memory models have proposed that high frequency words have better recovery (explaining better recall) whereas low frequency words have better sampling (explaining better recognition). Therefore, word frequency was manipulated to test neo-classic interference theory.

Within neo-classic interference theory the independent cue recall task may be viewed as a direct test of recovery interference. As the independent cue is a pre-experimentally associated cue that is only used at final recall, there is no experimentally induced sampling interference for the independent cue. Thus, with the presentation of an independent cue for recall any observed forgetting is uniquely attributed to recovery interference. Therefore, the extent to which there is impaired recall in the independent cue task is diagnostic of recovery interference.

Because recovery interference is assumed to be cue-independent, any observed recovery interference effects in independent cue recall should also be observed in original cue recall. However, the neo-classic interference theory does not necessarily predict equivalent accuracy rates for independent and original cue recall. As original cue recall has the potential for sampling interference as well as recovery interference, the magnitude of forgetting in the original cue recall may be much larger than independent cue forgetting. To the extent that original cue forgetting demonstrates a greater magnitude of forgetting than independent cue forgetting, this is diagnostic of sampling interference. The neo-classic interference theory, therefore, uses independent cue recall to be diagnostic of recovery interference effects, which may then be used to be diagnostic of sampling effects using original cue recall results. The degree of independent cue forgetting indicates how much of original cue forgetting is due to recovery interference. However, if no independent cue forgetting is observed, then neo-classic interference theory may still predicts original cue forgetting as participants are still learning to associate an alternate memory with the original cue.

One implication of this theoretical constraint is that the neo-classic interference theory always predicts original cue forgetting will be equivalent to, or greater than, independent cue forgetting. Thus, the model allows for three possible data patterns: recovery interference without sampling interference (i.e., similar magnitudes of original and independent cue forgetting), sampling interference without recovery interference (i.e., original cue forgetting but no independent cue forgetting), and both sampling and recovery interference (i.e., independent cue forgetting and even greater original cue forgetting).

If low-frequency words have low initial recovery strength, as many memory models assume, this should lead to a lower probability of recall, as recall is dependent upon both successful sampling and successful recovery. To the extent that a partial memory is sampled and a new recovery is learned in suppression training (i.e., participants used an ‘indirect’ suppression learning route rather than directly associating the new response with the cue), low-frequency words should be more susceptible to recovery interference than high-frequency words. In contrast, high frequency words are expected to have weaker sampling, and thus be susceptible to sampling interference. Thus, suppression induced forgetting should primarily load onto independent cue testing for low frequency words, which will also entail loading onto original cue. This leads to a prediction of a greater rate of forgetting for low-frequency suppressed items compared to high-frequency suppressed items in independent cue recall. In contrast, suppression induced forgetting should primarily load onto original cue testing for high frequency words (and less so independent cue recall). High frequency suppressed items should show greater forgetting than low frequency words due to sampling interference in original cue recall. However, this difference may not be noticeably different depending on how strong recovery interference is for the items since low frequency items are assumed to have greater recovery interference. Thus, the expectation is a 3-way interaction between task type (baseline, no-think, press-enter, and recall), word frequency, and the cue used to test memory (independent versus original).

Participants

One hundred forty three participants were recruited from the University of Maryland’s psychology undergraduate population and received extra credit in a psychology course they were enrolled in for their participation.

Materials

The word stimuli used were taken from the University of South Florida word association database (Nelson, 1998). All words were 3-8 letter nouns. There were 96 total word triads with each triad consisted of a medium-frequency independent cue word that was associated with two target words, one low- and one high-frequency word, with a forward association strength between .04 and .1. The cue words were of medium Kucera-Francis frequency range of 11 – 50 with the low-frequency target words, the Kucera-Francis frequency was between 2 and 10 while the high-frequency target words had a Kucera-Francis frequcncy range of 51 – 1772.

Design and Procedure

The procedures for Experiment 2 were identical to Experiment 1 with the following exceptions: (1) Selection of the word stimuli (see above materials section); (2) frequency of the target word stimuli was manipulated; (3) 48 rather than 40 cue-target word pairs were used; (4) half of the target words were tested with original cue and the other half tested with independent cue final recall; (5) no initial learning manipulation occurred; (6) the correct target word response for the recall cues was not provided as feedback during suppression training and; (7) no recognition occurred after the independent cue recall. These changes are discussed in more detail below.

The experiment maintained the four phases of Experiment 1: initial learning, suppression training, original cue recall and independent cue recall. The initial learning was identical to Experiment 1 with the exception that there was no manipulation of learning and all target words were required to be correctly recalled once before the participant could move on to the next phase. Participants saw 48 total cue-target word pairs, yet there were 96 total word triads. Each word triad contained one low-frequency target word, one high-frequency target word and one medium-frequency cue word that was similarly associated to both the low and high-frequency target words but was minimally associated with any other target words. Forty-eight word triads were randomly selected (without replacement) for each participant to be used as cue words and the other 48 were used for target words and independent cues: One target word (low- or high-frequency) was semi-randomly selected from the 48 of the target word triads such that there was an equal number of low (24) and high (24) frequency word targets. When presented as cue-target word pairs the cue words and the target words were unassociated. Experiment 2 also increased the number of cue-target word pairs from 40 in Experiment 1 to 48 since each task (baseline, recall, no-think and press-enter) is now being divided into low- and high-frequency words making the individual analyses have 3 observations for each word task condition in the respective final recall tests (since only half of each word task condition is going to be used in original cue recall and half in independent cue recall)[2].

In suppression training there were still three tasks: recall, no-think and press-enter. The no-think and press-enter items all received the same feedback in experiment 1 but the recall items did not receive the correct target word as feedback if the participant did not correctly recall the target word. The recall items still received feedback on whether their response was correct and informed if they needed to recall the target word, but they were not provided with the correct target word as feedback. This change was made in order to see if the recall items would exhibit an effect of

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[2] Initially we tried using 64 word pairs for a total of 4 observations for each word task in same-cue and independent cue recall but participants were having a difficult time recalling 64 word pairs and were taking a very long time to finish the task.

word frequency but Experiment 1 had such high rates of correct recall for response items it seemed unlikely an effects of word frequency would be observed with such high recall rates. By removing the feedback of the correct target word, the recall accuracy for recall items may show less of a ceiling effect and allow for an assessment of word frequency with the recall items.

After suppression training participants engaged in original cue recall with half of the items, for a total of 24 word cues: half of the low-frequency baseline items (3 items), half of the high-frequency baseline items, half of the low-frequency recall items, half of the high-frequency recall items (3 items), half of the low-frequency no-think items (3 items), half of the high-frequency no-think items (3 items), half of the low-frequency press-enter items (3 items) and half of the high-frequency press-enter items (3 items). The original cue recall items were randomly selected from all of the word pairs and the remaining word pairs were used for independent cue recall. Lastly, independent cue recall followed original cue recall with 24 word cues. The remaining items that were not used in the original cue recall were used in the independent cue recall. This procedural change was implemented in order to ensure that words were not being used in both original and independent cue recall as there might be a possibility of engaging in original cue recall first affecting subsequent independent cue recall.

Results and Discussion

A 2 (word frequency: high or low) x 4 (task type: baseline, respond, no-think and press-enter) ANOVA was conducted for each final memory test (original cue and independent) followed by comparison tests.

The neo-classic interference theory expected a three-way interaction between task type, word frequency, and recall test. However, there were no two-way interactions of task type and word frequency for either original cue recall or independent cue recall accuracy. Thus, the effect of word frequency on task type and recall type was not able to be assessed as the tree-way interaction between task type, word frequency, and final recall cue was unable to be assessed. In the following section the main effects of task type are reported as well as the word frequency results.

Independent Cue Recall

The neo-classis interference theory is only constrained in regard to word frequency when comparing independent and original recall, but it does not make a particular prediction for one of these tests in isolation. The theory is not constrained in its predictions for frequency effects in independent cue recall due to the difficulty in simultaneously predicting the affect of frequency on recovery during suppression training, which would affect subsequent recall. There was a main effect of word frequency, $F(1, 142) = 16.76$, $p = < 0.001$, ES = 0.12 and rows 2 and 4 of Table 2 shows high-frequency words are recalled less than low-frequency words.

The neo-classic interference theory does expect a main effect of task type on independent cue recall accuracy, which was observed $F(3, 426) = 3.2$, $p < 0.05$, ES = 0.02. Specifically, the neo-classic interference theory predicts that no-think and press-enter instructions should lead to similar recall performance and these conditions should have worse recall compared to baseline and recall conditions.

Retrieval Type	Recall	No-Think	Press-Enter	Baseline
	High Word Frequency			
Original Cue Recall	.79 (.02)	.70 (.03)	.68 (.03)	.77 (.02)
Independent Cue Recall	.37 (.03)	.33 (.03)	.35 (.03)	.32 (.03)
	Low Word Frequency			
Original Cue Recall	.70 (.03)	.64 (.03)	.64 (.03)	.70 (.02)
Independent Cue Recall	.46 (.03)	.37 (.03)	.41 (.03)	.40 (.03)

Table 2. Experiment 2 mean accuracy by task, condition and memory strength with observed standard errors in parenthesis

A dependent t-test revealed no significant differences between the no-think and press-enter tasks and the Bayes t-test showed some evidence for the null hypothesis with a value of 7.82, indicating that the null hypothesis is 7 times more likely than the alternative hypothesis. Because the no-think and press-enter tasks do not appear to differ significantly, with either in NHST or Bayes t-test, these were collapsed for subsequent analyses. As expected, performance on the no-think and press-enter conditions was significantly lower than the recall condition, $t(142) = 2.82$, $p < 0.01$, ES = 0.23, however these conditions were not significantly lower than the baseline condition, $t(142) = -0.12$, $p > 0.05$. Since independent cue recall for the no-think and press-enter conditions were not significantly different from the baseline condition, there is no evidence of recovery interference as a result of suppression training in this experiment.

Original Cue Recall

Neo-classic interference theory expects a main effect of word frequency for independent cue recall, with low-frequency words being recalled less often than high-frequency words. This is an expectation of replication of previous literature (Deese, 1960; Hall, 1954; Sumbly, 1963). This expectation was confirmed, $F(1, 142) = 18.14$, $p < 0.001$, ES = 0.12, and rows one and three of Table 1 show that high-frequency words being recalled more often than low-frequency words.

As there was no forgetting recall impairment observed in the independent cue recall, the neo-classic interference theory there is less constrained in its predictions for task type and original cue recall. Because there was no independent cue forgetting, the theory predicts that any observed original cue forgetting is only due to sampling interference. There was a main effect of task type on cued-recall accuracy, $F(3, 426) = 8.91$, $p < 0.001$, ES = 0.06. As a main effect was observed, the neo-classic interference theory would then expect that the no-think and press-enter conditions would not differ in recall accuracy and would be impaired relative to baseline and recall conditions. A dependent t-test revealed no significant differences between these two tasks and the Bayes t-test showed strong evidence in support of the null hypothesis with a factor of 13.91, indicating that the null hypothesis is almost 14 times more likely than the alternative hypothesis. Because the no-think and press-enter tasks do not appear to differ significantly, with either in NHST or BIC criterion, these were collapsed for subsequent analyses. As expected, performance in the no-think and press-enter conditions was significantly less than the baseline, $t(142) = 3.96$, $p < 0.001$, ES = 0.30, and recall conditions, $t(142) = 5.02$, $p < 0.001$, ES = 0.35.

Thus, from an interference viewpoint, Experiment 2 demonstrated sampling, but not recovery, interference. This is shown in the recall impairment for the original cue recall of items that received no-think and press-enter training, but no recall impairment for these items with independent cue recall. As the independent cue results demonstrate that there was no recovery interference due to suppression training, the differential effects of recovery interference on word frequency could not be assessed.

This study emphasizes that recovery interference may be a small effect as it is often hard to observe and replicate cue independent forgetting (Bulevich, Roediger, Balota, & Butler, 2006). This difficulty in finding cue independent forgetting experimentally is understandable from a neo-classic interference standpoint. Cue-independent forgetting relies on a delicate balancing of memory strength such that the memories need to be strong enough that the person automatically samples the partial memory of the target before recovering that partial memory to an alternate completion in order to produce competing recoveries. On the other hand the memory needs to be weak enough to allow for interference from competing recoveries, if the memory recovery for the target is too strong it won't show any interference effects as it effectively 'wins' every competition with alternate recoveries.

Therefore, there is an expected non-monotonic relationship with memory strength and forgetting. Where this delicate balance lies within the word frequency and memory strength spectrum is something that needs further exploration. Experiment 2 demonstrates that this cue independent forgetting effect is fragile and perhaps the words used were too extreme in their normative frequency to reveal recovery interference.

Chapter 4: Experiment 3

Introduction

Experiment 1 provided support for the neo-classic interference theory within the think/no-think paradigm. However, Experiment 2 provided an inconclusive test of neoclassic interference because it failed to produce any independent cue forgetting for either low or high frequency words. Experiment 3 was to designed to test predictions of interference theory in a paradigm other than the think/no-think paradigm. In Experiment 3 a modified retrieval induced forgetting paradigm was employed in order to more clearly assess whether participants are learning an alternate response that interferes with later recall by: (1) not using categorical lists for learning and instead using a list of unassociated word triads (i.e., cue word: plane, target word 1:doctor and target word 2: grape, see Figure 6 and Table 3); (2) using only low-frequency words for target words and; (3) having participants selectively retrieve one of the target words when presented with an independent cue for that target memory (i.e., "nurse – do__", see Figure 6 and Table 3). It is particularly important to note that instead of independent cue recall as a final test, independent cue recall was used as a suppression method. In this way, recovery strength of items may be directly affected in a way that does not necessitate any inhibition of alternatives. Because the independent cue is used for retrieval practice, it is unique to one experimental item and there are no other experimental items competing for access during retrieval that would require inhibition.

For example, in the initial learning phase participants may learn "plane → doctor AND grape" as well as "ordeal → roach AND car." Due to the simultaneous learning of the cue-target-target triads, it is possible that the target memory traces will become associated (likely to a weak extent) with the alternate memories recovery. Thus, there are two possible 'paths' for correct recall of a target when presented with the cue. The first path of correct recall is the 'direct' route where the correct target memory trace is sampled followed by the correct recovery (i.e., target memory 1 is sampled and is recovered correctly to target memory 1). The second path of correct recall is the 'indirect' route where the alternate memory trace is sampled, but the correct target is still retrieved (i.e., target memory 2 is sampled and is recovered to target 1). For example, if a participant learned "plane" – "doctor" and "grape", a direct route of learning would be when a participant sampled "d_ct_r" and recovered "doctor" in response to "plane." An indirect learning route would be when a participant sampled "g_a_e" and recovered "doctor" in response to "plane".

As a result of the retrieval practice of *one* of the target items after initial learning, interference theory predicts that the practiced items will have increased recall accuracy while the non-practiced items will have recall impairment relative to baseline items where neither target was practiced. For the *non-practiced* items the probability of recall decreases to the extent that the 'indirect' route is utilized. Because the practiced (i.e., alternate) memory trace has had recovery practice of its correct recovery, the non-practiced memories are weaker competitors for recovery when this alternate memory trace it sampled. This means that the non-practiced items will have a decreased probability of recall, compared with baseline, when the indirect route is used. This leads to a lower probability of recall than baseline (see Table 10 below and model discussion for theoretical and mathematical elaboration).

Continuing the earlier example, retrieval practice with "doctor" should, therefore, lead to an increased probability of recalling "doctor" when presented with "plane – do___" and a decreased probability of recalling "grape" when presented with "plane – gr___." This recall benefit and impairment is relative to recall of "ordeal-ro___" and "ordeal-ca____" where neither "roach" nor "ideal" received retrieval practice. This pattern of forgetting is predicted even though in learning to recover "doctor" when presented with "nurse," the participant should have little reason to strengthen the association between "plane" and "doctor" so the association between the cue-target should not lead to a decrease in the recall of "grape." Thus, there is little reason to believe that in learning "nurse-doctor" that the link between "plane-doctor" is being strengthened, which would lead to competition with the link "plane-grape." Any observed forgetting of "grape" in comparison to baseline triads may be uniquely attributable to increased recovery strength as a result of retrieval of the word "doctor."

The logic for Experiment 3 is similar to Experiment 1 and 2 in that the learning of one recovery will result in the detriment of another recovery. Given that final recall is probed with the original cue plus target word stem, all items are assumed to have the same sampling strength at final recall, which uniquely leaves recovery strength as the possible mechanism driving recall performance differences. Neo-classic interference theory predicts original cue recall differences with greater recall accuracy for practiced target words, and impaired recall for non-studied target words compared to baseline words. Thus, to the extent that these differences in recall accuracy are observed, these results may be uniquely attributed to differential recovery strengths. This is a novel paradigm and, to our knowledge, is the only study to empirically assess the recovery process directly.

Participants

One hundred thirteen participants from the University of Maryland and were given extra credit in a psychology course for their participation.

Materials

Sixty target words were taken from the University of South Florida word association database (Nelson, 1998) and the low-frequency words had a similar frequency range as the low-frequency (2 – 10) words used in Experiment 2. The thirty cue words were medium-frequency words with a similar frequency range (11 – 51) as the cue words used in Experiment 2.

Design and Procedure

The study was a within subjects design with three word conditions: Practiced, non-practiced and baseline words. The study was entirely computerized.

There were three phases to the experiment: initial learning and retrieval, selective retrieval, and original cue recall (see Figure 6 and Table 3). The initial learning phase presented participants with the thirty cue-target-target word triads at a rate of 5 seconds per pair in the center of the computer screen in an order randomly determined for each participant. Next, participants performed cued-recall testing for both target words to assess the degree of initial learning. Participants were tested with each cue word and the first letter of the target word (i.e., plane – d____ and plane – g___) and were informed whether their typed response was correct. If incorrect, they were informed of the appropriate response to allow further learning. This test list was repeated in random order as cue words were progressively eliminated from the test once the target word had been correctly recalled once.

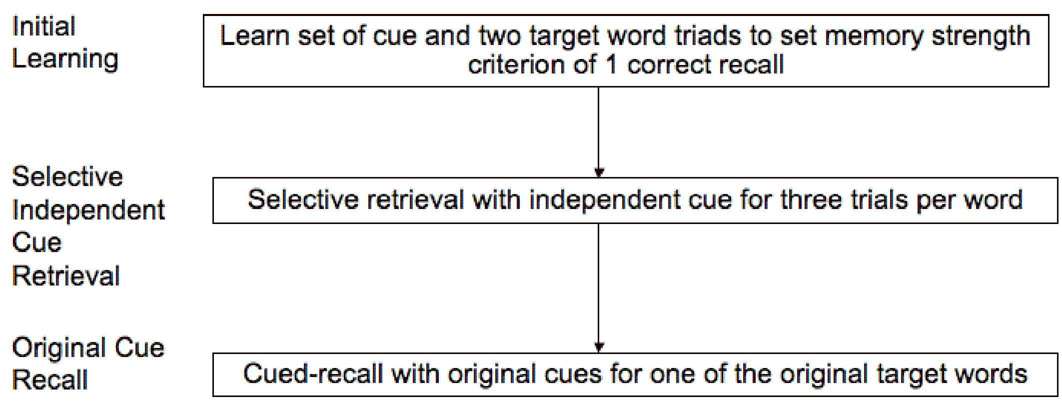

Figure 6. Modified retrieval induced forgetting paradigm for Experiment 3

Word Conditions	Initial Learning	Selective Recall	Final Recall
Baseline	Ordeal Roach Car	No target word (neither roach nor sunshine) is practiced in the selective recall stage (number 3)	Roach or Sunshine will be randomly selected to be tested at final recall: Ordeal – R____ or Ordeal – S_____
Practiced	Plane Doctor Grape	Nurse – Do_____	Plane – Do____
Non-Practiced	Grass Mouse Butter	Bread – Bu_____	Grass – Mo_____

Table 3. Example of modified retrieval induced forgetting paradigm for Experiment 3

The second phase was selective retrieval where all 20 of the practiced target words received retrieval practice. The selection of which word triads were baseline triads or practice triads was randomly determined for each participant. For retrieval practice participants were presented with an independent cue of the practiced target word and the first two letters of the target word, such as “Nurse – Do_____” and participants were asked to fill in the blank. Participants practiced retrieval on these 20 words three times per word in a random order. The selection of which target word was the practiced item and which item was the non-practiced item was randomly determined for each word pair.

The third and final phase was a surprise cued-recall that tested all 30 of the cue words from initial learning. Cues were presented one at a time in random order with the first two letters of one of the target words and the participants were asked to recall the corresponding original target word. From the baseline condition the target memory for final recall were randomly selected from each triad, from the practiced words half of the words were randomly selected and the other half had the non-practiced word selected for attempted recall in the final phase (see Table 3 for an example). It was stressed that accuracy was highly desirable, regardless of any previous instructions.

Results and Discussion

A one-way ANOVA was conducted for task type (baseline, practiced, and non-practiced) for the final memory test (original cue), followed by comparison tests.

Final Recall

As expected by neo-classic interference theory, there was a significant effect of task type on cued recall accuracy, $F(2, 224) = 53.97$, $p < 0.001$, ES = 0.33 (see Figure 7). Also as expected, and as can be seen in row 1 of Table 4, the practiced words were recalled significantly more often than both the baseline, $t(112) = 8.46$, $p < 0.001$, ES = 0.77, and non-practiced words, $t(112) = 8.71$, $p < 0.001$, ES = 0.80. However, to the extent that the indirect route is used, neo-classic interference theory expects the non-practiced items to be recalled less than the baseline words and this was marginally significant, $t(112) =$, $p = 0.09$, ES = 0.09. As can be seen in row 1 of Table 4, the non-practiced words being recalled less often than baseline words, but not significantly.

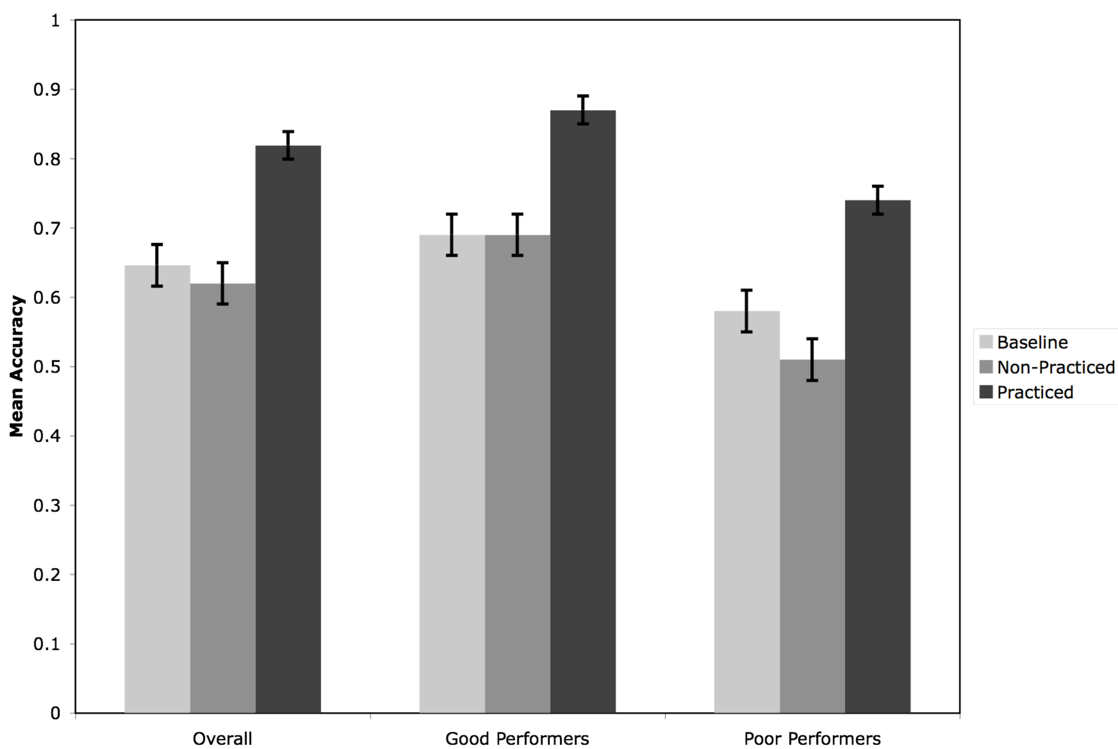

Figure 7. Experiment 3 mean accuracy of original-cue recall for the three word tasks by performance on retrieval practice: overall, good, and poor performance levels.

	Practiced	Non-Practiced	Baseline
Overall	.82 (.02)	.62 (.03)	.65 (.03)
Good Retrieval Practice Accuracy	.87 (.02)	.69 (.03)	.69 (.03)
Poor Retrieval Practice Accuracy	.74 (.03)	.51 (.05)	.58 (.04)

Table 4. Experiment 3 mean accuracy by task, with observed standard errors in parenthesis

Final Recall Conditional on Retrieval Practice Accuracy

If a participant has learned the word triads well, they may have a high initial learning strength of the word triads (i.e., the items all have a strong initial sampling and recovery strength) thus a higher likelihood of *only* using the 'direct' route of retrieval. These items will then be easily recovered during the independent cue retrieval practice, which will increase their recovery strength while decreasing the recovery strength of the non-practiced counter-part in the indirect route (see below model discussion of this experiment for a the mathematical equations deriving this prediction). If the participants who have learned the items to a greater degree are able to easily recall items during retrieval practice, they are more likely to use the direct route of recall and never sample the alternate memory trace. This means there will be no recovery interference because no alternate recoveries were learned or used for participants who perform well on the retrieval practice.

Given the very high rates of final recall, the paired sample t-tests were also conducted conditional upon word retrieval practice accuracy. Participants who had 90% accuracy or lower on the word retrieval practice were considered to have "worse" performance on the retrieval practice while participants who had over 90%

accuracy on the word retrieval practice were considered to have “better” performance. The neo-classic interference theory predicts that participants who have greater accuracy on the retrieval practice will show no recall decrement for the non-practiced items relative to the baseline items. The data support this prediction as there was no significant difference between baseline and non-practiced words for better performers, $t(69) = 0.07$ (see Table 4 and Figure 7).

Conversely, the participants who do worse on the retrieval practice should show significant recall impairment for non-practiced items compared to baseline items. The data also support this prediction, as there was a significant difference between baseline and non-practiced words for worse performers, $t(42) = 1.80$, $p < 0.05$, ES = 0.23. As can be seen in rows 2 and 3 of Table 4, as well as in Figure 7, the non-practiced words were recalled less than baseline words.

Lastly, the practiced condition is expected to show significantly greater recall accuracy than the non-practiced and baseline items due to the increased recovery strength of the practiced item. This was confirmed as the practiced words were recalled significantly more often than the baseline for both the participants who performed better on the retrieval practice, $t(69) = 7.67$, $p < 0.001$, ES = 0.89 and the participants who performed worse on the retrieval practice, $t(42) = 4.23$, $p < 0.001$, ES = 0.57. The recall condition also had a significantly higher recall than the non-practiced items for both the better performers, $t(69) = 7.08$, $p < 0.001$, ES = 0.81, and the worse performers $t(42) = 5.24$, $p < 0.001$, ES = 0.79.

These results from show the benefit of retrieval practice of items on subsequent recall: The practiced items are better recalled than baseline and non-practiced words. The retrieval practice benefit may at first glance appear to be an obvious outcome: Practicing items lead to better subsequent recall of the items. This result is similar to the traditional retrieval induced forgetting finding of increased recall for practiced items (Bjork, Bjork, & Anderson, 1994). However, this result differs from traditional retrieval induced forgetting practice effects where the retrieval practice is done with the original cue (which is also a weak independent cue). The paradigm used in Experiment 3 employed unique independent cues for retrieval practice and the recall benefit was observed with the original cue plus target word stem for recall, which is not a semantic associate of the target. It appears that practicing a word leads to better recall of that word later, regardless of type of cue used.

Thus, Experiment 3 found support for the neo-classic interference theory in the finding that retrieval practice benefits subsequent recall. Further support was found as the predictions from neo-classic interference theory were confirmed by the split-half recall analyses: The difference between baseline and non-practiced words recall is dependent upon how successful the participant was at the retrieval practice. As expected, those participants who were more successful with the retrieval practice showed no interference effects, as there was no difference between baseline and non-practiced words. Conversely, the participants who were not as successful with the retrieval practice did show interference effects as exemplified by non-practiced items being recalled significantly less than baseline items. Moreover, this modified retrieval induced forgetting paradigm was the first attempt, to our knowledge, to directly assess the recovery process.

Chapter 5: Search of Associative Memory with Recovery Interference (SAM-RI) Model and the Think/No-Think Paradigm in Experiment 1

In order to demonstrate the ability of interference theory to explain empirical results, an interference based global memory model based on the search of associative memory (SAM) model is elaborated. This model is the mathematical implementation of the neo-classic interference theory, so it adds recovery interference to the original SAM model. Therefore, the neo-classic interference model will be called the search of associative memory model with recovery interference (SAM-RI). SAM-RI is used to model the results from the think/no-think paradigm used in Experiment 1 as well as the results from the modified retrieval induced forgetting paradigm used in Experiment 3. The results from Experiment 2 were not modeled, as Experiment 2 results indicated that there is no recovery interference to model. The SAM-RI model will be specified to capture to the findings from the retrieval induced forgetting literature.

The SAM model has been applied to both recall (Raaijmakers & Shiffrin, 1981) and recognition (Gillund & Shiffrin, 1984) and can be used to model all of the results from Experiment 1. First a description of the essential model assumptions, equations and applications to the think/no-think paradigm will be presented before the behavioral data from Experiment 1 is modeled.

In fitting the data from Experiment 1, the SAM-RI model used 6 free parameters (Weak, Strong, Recall, Other, Association, and Variance, see Table 5) and one fixed parameter (Kmax = 1). SAM-RI uses two learning parameters, W and S, to reflect the differential experimental learning of the weak (i.e., items that were correctly recalled once in initial learning) and strong (i.e., items that were correctly recalled three times in initial learning) items. The recall parameter, R, represents the additional sampling and recovery strengthening in the suppression training for those items that receive retrieval practice (i.e., the recall items). Similarly, the other learning parameter, O, represented the additional sampling strengthening and simultaneous recovery decrement for those items that receive "other learning" of the no-think and press-enter responses. The final two parameters, A and V, are used to model the independent cue sampling strength and derive variance distributions for recognition respectively. The SAM-RI model employs these 6 free parameters to simultaneously fit the observed 24 average accuracy values from the original cue recall, independent cue recall, and recognition.

In the SAM-RI model the probability of retrieval is assumed to rely upon *both* sampling and recovery. Retrieval is the probability of sampling multiplied by the probability of recovery, with recovery being dependent upon sampling:

$$p(\textit{retrieve}) = p(\textit{sample}) * p(\textit{recover}|\textit{sampling}) \qquad \text{Equation 1}$$

where p(retrieve) means recall on a particular retrieval attempt. Recall may include multiple retrieval attempts, which necessitates a stopping rule for retrieval attempts. The SAM stopping rule is implemented in the parameter Kmax, where (Raaijmakers & Shiffrin, 1981) Kmax is a fixed parameter that allows for participants to have up to

Kmax retrieval attempts for recall: Regardless of the success of the Kmax retrieval attempt, retrieval will be terminated. The probability of recalling an item is made dependent upon the probability of retrieval (Equation 1): Failure to recall an item is the failure to retrieve across all retrieval attempts ($(1\text{-}p(retrieve))^{Kmax}$), making the prediction for recall accuracy:

$$p(recall) = (1\text{-}(1\text{-}p(retrieve))^{\text{Kmax}}) \qquad \text{Equation 2}$$

However, when Kmax = 1 the probability of recall (Equation 2) reduces to the probability of retrieval (Equation 1), as is the case in Experiment 1. As there is one unique cue for each target memory in Experiment 1, this reduces the Kmax parameter to 1.

Parameter	Description	Paradigm
B, S, W	Learning strength of association between cue and memory trace (sampling) and memory trace and recovery (recovery): Baseline, Weak, and Strong learning strengths for differing amounts of learning	Think/No-Think & Retrieval Induced Forgetting
R	Recall practice benefit that increases sampling strength and recovery strength for items that receive additional recall	Think/No-Think & Retrieval Induced Forgetting
O	Other learning that increases sampling strength and decreases recovery strength for items that are automatically sampled but then recovered to an alternate completion	Think/No-Think & Retrieval Induced Forgetting
A	Association strength between a cue and target based on pre-experimental association	Think/No-Think & Retrieval Induced Forgetting
V	Variance that is a constant of proportionality to specify the amount of normally distributed variance associated strength of self-sampling for recognition	Think/No-Think

Table 5. Descriptions and notation of parameters used in the SAM-RI model for modeling Experiment 1 and Experiment 3.

The probability of sampling is assumed to follow the Luce choice rule for stochastic sampling (Luce, 1959). Sampling is dependent upon the ratio of the strength of association between the cue to the target memory trace by the possible sample space for that cue. The possible sample space for sampling, or SS_S, is considered the summation of the strength of associations between all memory traces associated with the cue, with the value of 1 represented the non-experimental associations (see Tables 6 and 7):

$$p(sample_i) = \frac{S(C,T_i)}{S(C,T_i) + \sum S(C,T_j) + 1} \quad \text{Equation 3}$$

where j ≠ i. The learned strength of association between the cue and the target memory trace is represented by the term $S(C,T_i)$ while other learned associations between the cue and other memory traces is represented by $S(C,T_j)$. In this general sampling equation, the cue (*C*) may be the context, the original cue, an independent cue or some internally generated cue, while *T* refers to the memory trace. The value of 1 represents the pre-experimental associations between the cue and other memory traces.

In Experiment 1 there is one unique cue for each target memory, which would result in the term for the association between the cue and other experimentally learned memory traces ($S(C,T_j)$) being zero. While it is possible that there is some "other" learned association in sampling due to the suppression training, we assume that this other memory is not included in SS_S due to the instructions during final recall. The recall instructions establish the context used to guide sampling: participants are instructed to revert to the original target memory recall. This sets up a contextually defined sample space that eliminates any other memories learned during suppression training and results in the $\Sigma S(C,T_i)$ term being zero (see Table 6):

$$p(sample_i) = \frac{S(C,T_i)}{S(C,T_i)+1} \qquad \text{Equation 4}$$

Sampling strength depends on the experimental condition type (i.e., recall, no-think, press-enter, and baseline) as well as the type of recall cue used to probe for the target memory: Original cue, independent cue, or self-cue (for recognition). For the original cue recall the sampling strength is dependent upon how many times the cue and target word been successfully paired, or recalled, together in initial learning and suppression training. For example, in Experiment 1 there will be a stronger sampling strength for the words learned to three correct recall (represented by the parameter S for strong learning) than for the words learned to one correct recall (represented by the parameter W for weak learning). For simplicity we assume that initial learning strengthens sampling and recovery strengths to similar degrees (i.e., $S(C,T_i) = S(T,R_i)$, see Table 6)[3]. For independent cue recall, sampling is based solely on the pre-experimental strength of the association between the independent cue and the target memory (represented by the parameter A for pre-experimental association so that $S(C,T_i)$ = A, see Table 7). For the self-cue in recognition, SAM uses sampling strength to derive normally distributed unequal variance target and distractor distributions.

[3] In general, sampling and recovery need not be coupled in this fashion. We ran the model with separate learning rates for sampling and recovery in the recall condition, which requires an additional free parameter. While this model fit the data slightly better, it was not substantially different from the simpler model and so we omit it for reasons of clarity.

	p(sample)	p(recover)	p(retrieve)
Baseline, Weak Memories	$(\frac{W}{W+1})$	$(\frac{W}{W+1})$	$(\frac{W}{W+1})^2$
Recall, Weak Memories	$(\frac{W+R}{W+R+1})$	$(\frac{W+R}{W+R+1})$	$(\frac{W+R}{W+R+1})^2$
No-Think, Weak Memories	$(\frac{W+O}{W+O+1})$	$(\frac{W}{W+O+1})$	$(\frac{W+O}{W+O+1})*(\frac{W}{W+O+1})$
Press-Enter, Weak Memories	$(\frac{W+O}{W+O+1})$	$(\frac{W}{W+O+1})$	$(\frac{W+O}{W+O+1})*(\frac{W}{W+O+1})$
Baseline, Strong Memories	$(\frac{S}{S+1})$	$(\frac{S}{S+1})$	$(\frac{S}{S+1})^2$
Recall, Strong Memories	$(\frac{S+R}{S+R+1})$	$(\frac{S+R}{S+R+1})$	$(\frac{S+R}{S+R+1})^2$
No-Think, Strong Memories	$(\frac{S+O}{S+O+1})$	$(\frac{S}{S+O+1})$	$(\frac{S+O}{S+O+1})*(\frac{S}{S+O+1})$
Press-Enter, Strong Memories	$(\frac{S+O}{S+O+1})$	$(\frac{S}{S+O+1})$	$(\frac{S+O}{S+O+1})*(\frac{S}{S+O+1})$

Table 6. Prediction equations in terms of SAM-RI parameters for original cue recall in Experiment 1.

Further, with original cue recall, sampling also depends on the experimental word condition; recall, no-think, press-enter, and baseline. In the initial learning it is assumed that sampling strength is increased with successful sampling, which leads to the differential learning parameters, S for strong items and W for weak items. For original cue recall these sampling strengths remain the same (at S or W) only for the baseline items. Items that receive recall practice during the suppression training (recall items) are assumed to have greater sampling strength at final recall. This increased sampling strength is instantiated in the model by adding the parameter R to the original sampling strength of the recall items (i.e., the original cue sampling strength will be S+R for strong items and W+R for weak items).

	p(sample)	p(recover)	p(retrieve)
Baseline, Weak Memories	$(\frac{A}{A+1})$	$(\frac{W}{W+1})$	$(\frac{A}{A+1})*(\frac{W}{W+1})$
Recall, Weak Memories	$(\frac{A}{A+1})$	$(\frac{W+R}{W+R+1})$	$(\frac{A}{A+1})*(\frac{W+R}{W+R+1})$
No-Think, Weak Memories	$(\frac{A}{A+1})$	$(\frac{W}{W+O+1})$	$(\frac{A}{A+1})*(\frac{W}{W+O+1})$
Press-Enter, Weak Memories	$(\frac{A}{A+1})$	$(\frac{W}{W+O+1})$	$(\frac{A}{A+1})*(\frac{W}{W+O+1})$
Baseline, Strong Memories	$(\frac{A}{A+1})$	$(\frac{S}{S+1})$	$(\frac{A}{A+1})*(\frac{S}{S+1})$
Recall, Strong Memories	$(\frac{A}{A+1})$	$(\frac{S+R}{S+R+1})$	$(\frac{A}{A+1})*(\frac{S+R}{S+R+1})$
No-Think, Strong Memories	$(\frac{A}{A+1})$	$(\frac{S}{S+O+1})$	$(\frac{A}{A+1})*(\frac{S}{S+O+1})$
Press-Enter, Strong Memories	$(\frac{A}{A+1})$	$(\frac{S}{S+O+1})$	$(\frac{A}{A+1})*(\frac{S}{S+O+1})$

Table 7. Prediction equations in terms of SAM-RI parameters for independent cue recall in Experiment 1.

For the items in the suppression conditions, the original target memory is sampled only to the extent that it is unavoidably sampled through automatic processes. A more direct “pathway” involves direct association between the presented cue word and the correct alternative behavior. However, on some trials, the original target memory may be sampled, thus eliciting indirect learning to the press-enter or no-think recoveries by way of the target memory trace. Because this indirect pathway is less likely to be used, the parameter O is used for the degree of increased sampling of the target in the suppression conditions (i.e., the original cue sampling strength will be S+O for strong items and W+O for weak items), and it is expected that O will generally be less than R.

The probability of recovery is similar to that of sampling in that it is also assumed to follow the Luce choice rule for stochastic sampling (Luce, 1959). The SAM-RI model differs from the original SAM model by including a term in the total sample space for recovery that allows for recovery of other items (i.e., $S(T, R_j)$ in Equation 5 below). The recovery of other items was not needed in previous applications of SAM, but cue-independent forgetting indicates that this term may now be necessary. Recovery is assumed to be dependent upon the ratio of the correct target recovery to all possible recovery responses, which includes the target, any other response (such as no-think or press-enter), and the comparison value of 1 for recovery of anything else besides these responses (see Equation 4, Tables 6 and 7):

$$p(recover_i) = \frac{S(T,R_i)}{S(T,R_i) + \sum S(T,R_j) + 1} \qquad \text{Equation 5}$$

where $j \neq I$, T refers to the memory trace and R refers to recovery. Similar to sampling, the value 1 represents the baseline pre-experimental association of the memory trace to other recoveries. This recovery process is assumed to be the same for all cues as the cue only affects the sampling process.

However, just as the sampling process for original cue recall is dependent upon the experimental condition of the item, so is the recovery process. For items in the recall condition there will be both an increase in the original cue sampling strength and an increase in the target memory recovery strength. For simplicity it is assumed that sampling and recovery are strengthened to similar degrees and so the parameter R is added to both the initial sampling strength and the initial recovery strength for items in the recall condition (i.e., the sampling and recovery strength is S+R for strong items and W+R for weak items). On the other hand, each time a participant recovers an alternative completion (i.e., "no-think" or "press-enter") when they sample the target memory, it is assumed this is increasing the sampling strength but not the recovery strength. The sampling strength will increase by the parameter O, but there will be no corresponding increase in recovery as no successful recovery occurs. However, because an alternate recovery is learned the sample space for recovery, or SS_R, increases by O (i.e., $S(T,R_j) = O$). The no-think and press-enter suppression conditions are the only conditions that learn an alternate recovery, which results in these conditions having a positive value for the summation of the $S(T,R_j)$ term whereas this summation is zero in all other conditions. The result of this increased SS_R for the suppression conditions is decreased probability of recovery and, thus, a decreased probability of recall relative to all other conditions.

Finally, forced-choice recognition is based on the sampling strength for the target as a cue for itself (self-cue). The sampling strength for the self-cue is also set to S and W for initially strong and weak memories respectively. These same parameters are used because initial training involves corrective feedback upon failure to recall, allowing learning between the target word and the target memory trace. As the same procedure is employed in the recall condition where the target is continually recalled during suppression training, the self-sampling strength is increased by the value R for the recall condition (i.e., sampling strength for the self-cue is S+R for strong memories and W+R for weak memories). However, in the press-enter and no-think conditions, the target is not recovered and does not have any additional self-sampling which results in these conditions having the same self-sampling strength as baseline items. Thus, SAM-RI predicts a recognition benefit for the recall condition and neither a recognition deficit nor benefit for the suppression conditions. Finally, the distractor in the forced choice is another word that is equally associated to the independent cue; its self-sampling strength is also set to the parameter A in all conditions.

The SAM-RI model of recognition uses the above detailed sampling strengths to specify normally distributed unequal variance target and distractor distributions, just as in the original SAM model (Gillund & Shiffrin, 1984). Forced choice recognition accuracy is found through the distribution of the differences between the target (*tar*) and distractor (*dis*) self-sampling strengths (see Equation 6).

$$\text{p(correct)} = \int_0^\infty \varphi\left(x, \mu = (tar - dis), \sigma^2 = V\left[tar^2 + dis^2\right]\right)dx \qquad \text{Equation 6}$$

The integral is over the normal distribution (φ), with parameters μ and σ, evaluated from 0 to infinity. This provides the probability of correct recognition, which is equal to the probability that the distractor familiarity is less than the target familiarity. The parameter V, is a constant of proportionality to specify the amount of normally distributed variance associated with each additional unit of familiarity as dictated by the strength of self-sampling.

As seen in Table 8, with these 6 parameters the model provides a very accurate fit to all 24 of the observed average accuracy values. While the SAM-RI model has a chi-square goodness of fit of 37.86, and is technically rejected (chicrit=28.9 for 95% confidence), it should be noted that the number of data points is quite large (N=420; 84 participants with 5 observations per condition) and the fits to the data are numerically close. The best fitting values are: V = 0.3, A =1.2, W = 5.9, S = 13.4, R = 31.0 and O = 1.0. Notably, the other response (O) parameter is rather small compared to the recall learning (R) parameter, but this is a sensible discrepancy. This low O value is reasonable as the other response parameter is only incremented to the extent that people (mistakenly) automatically sample the original target memory, but then learn to recover an alternate memory, rather than directly associating the cue to the appropriate response.

Retrieval Type	Respond	No-Think	Press-Enter	Baseline
	Strong Memory Strength			
Original Cue Recall	.96 (.96)	.83 (.81)	.82 (.81)	.86 (.87)
Independent Cue Recall	.49 (.54)	.48 (.48)	.45 (.48)	.50 (.51)
Forced Choice Recognition	.96 (.96)	.95 (.95)	.96 (.95)	.94 (.95)
	Weak Memory Strength			
Original Cue Recall	.95 (.95)	.60 (.65)	.62 (.65)	.73 (.73)
Independent Cue Recall	.50 (.54)	.44 (.41)	.49 (.41)	.54 (.47)
Forced Choice Recognition	.96 (.96)	.92 (.92)	.93 (.92)	.94 (.92)

Table 8. Experiment 1 observed mean accuracy by task, condition and memory strength with predicted accuracy from the SAM-RI model in parentheses.

Lastly, the SAM-RI model assumes a fixed degree of sampling strengthening and recovery decrement for memories. However, while this simplifying assumption was adequate for Experiment 1, this assumption is likely to be false. The neo-classic interference theory relies on a delicate memory strength balance: the memory must be strong enough to be automatically sampled but weak enough to suffer from interference. If a memory is very weak then it will likely fail to produce automatic sampling, but if a memory is too strong it will overpower the newly learned alternate recovery and show no interference effects. Thus, there is a predicted non-monotonic relationship between initial memory strength and the degree of forgetting due to recovery interference. There will be little forgetting for very weak memories because the indirect pathway of automatically sampling the target memory will be rarely used and there will instead be a direct association between the cue and the suppression response. Conversely, very strong memories may elicit more other recovery learning for the suppression response, but the learned alternative will be insufficient to overpower the initially strong recovery response for the correct target. Thus, cue-independent forgetting requires memories of moderate strength that are strong enough to promote automatic sampling while still being weak enough for the detrimental effects of learned avoidance.

Chapter 6: Search of Associative Memory with Recovery Interference (SAM-RI) Model and the Retrieval Induced Forgetting Paradigm in Experiment 3

In Experiment 1 the model fits were of primary interest, but in Experiment 3 the primary interest is the parameter values rather than the data fitting. In fitting the data from Experiment 3, the SAM-RI model will employ 3 free parameters (Baseline, Recall, and Other, see Table 5) and one fixed parameter (Kmax = 3). Unlike Experiment 1, where there were two learning parameters (W and S), there is only one learning parameter needed for Experiment 3. Because all items received identical initial learning, the B parameter, which represents initial learning strength, was identical for all items. As in experiment 1, R represents the additional recovery strengthening for those items that receive retrieval practice (i.e., the practiced items), O represents the amount of learning associated with an 'indirect' route of learning. and Kmax represents the maximum retrieval attempts (Raaijmakers & Shiffrin, 1981).The free parameters used in Experiment 3, the baseline learning (B), other learning (O), and recall learning (R) parameters represent the different learning that occurs in the Experiment. The B parameter represents the sampling and recovery strength as a result of initial learning and all targets are assumed to have equivalent initial learning strength for sampling and recovery (i.e., $S(C,T_i)$ and $S(T,R_i)$ = B). The O parameter represents the amount of learning associated with using an 'indirect' route of learning. In Experiment 3 participants learn word triads where two target words are learned simultaneously, which leads to the potential for participants to use a direct (i.e., cue-sample target1-recover target1) and an indirect (i.e., cue-sample target2 – recover target1) route of learning. Thus, there are two possible paths for correct retrieval of a target when presented with the original cue. This leads to the probability of recall being the probability of retrieval given that the correct memory trace is sampled, plus the probability of retrieval given that the alternate memory trace is sampled (see Equation 4 and Table 9).

$$p(retrieval_i) = p(sample_i) * p(recover_i \mid sample_i) + p(sample_j) * p(recover_i \mid sample_j) \qquad \text{Equation 7}$$

Where *i* represents the target memory being probed for recall and *j* represents the alternate memory that was learned with the *i* target memory in initial learning. When the correct memory trace (T_i) is sampled and followed by correct recovery of $target_i$ (R_i), this is the 'direct' route of retrieval and is modeled in the first addition term for retrieval ($p(sample_i)*p(recover_i|sample_i)$). Conversely, when the incorrect memory trace (T_j) is sampled and followed by correct recovery of $target_i$ (R_i), this is the 'indirect' route of retrieval and is modeled in the second addition term for retrieval ($p(sample_j)*p(recover_i|sample_j)$).

The data from Experiment 3 yield three recall averages, one for each word condition; baseline, non-practiced, and practiced. Therefore, there are three prediction equations from the SAM-RI model (for baseline, practiced, and non-practiced average recall accuracy) and there are three free parameters. Given that the number of free parameters equals the number of data points to be fit, the fits are guaranteed to be, and are, perfect. However, neo-classic interference theory makes predictions regarding relative parameter values, hence the focus of the Experiment 3 modeling will be on the these predictions and the obtained parameter values.

	Direct Route p(retrieve)	Indirect Route p(retrieve)	p(retrieve)
Baseline	$(\frac{B}{B+O+1})*(\frac{B}{B+O+1})$	$(\frac{O}{O+B+1})*(\frac{O}{O+B+1})$	$(\frac{B}{B+O+1})^2+(\frac{O}{O+B+1})^2$
Practiced	$(\frac{B}{B+O+1})*(\frac{B+R}{B+R+O+1})$	$(\frac{O}{O+B+1})*(\frac{O}{O+B+1})$	$(\frac{B}{B+O+1})*(\frac{B+R}{B+R+O+1})+(\frac{O}{O+B+1})^2$
Non-Practiced	$(\frac{B}{B+O+1})*(\frac{B}{B+O+1})$	$(\frac{O}{O+B+1})*(\frac{O}{O+B+R+1})$	$(\frac{B}{B+O+1})^2+(\frac{O}{O+B+1})*(\frac{O}{O+B+R+1})$

Table 9. Prediction equations in terms of SAM-RI parameters for the average recall accuracy observed in Experiment 3.

The prediction equations for the probability of retrieval for the indirect route are nearly identical to the direct route of retrieval. However, the cue used at final recall is the original cue plus target word stem (i.e., the first two letters of one of the targets). The inclusion of the target word stem results in differing degrees of association between the recall cue and the two target memories. It is assumed that the correct target memory trace (T_i) will have a higher strength of association with the cue (i.e., a high sampling strength) than the alternate target memory trace (i.e, $S(C,T_i) > S(C,T_j)$). The probability for sampling in the indirect route is then the ratio of the strength of association between the cue and the alternate memory trace to the sample space of possible memory trace samples (i.e., SS_S, see Equation 8 and Table 9).

$$p(sample_j) = (\frac{S(C,T_j)}{S(C,T_i)+S(C,T_j)+1}) \qquad \text{Equation 8}$$

Where C is the cue being used to probe memory for the target memory i, and T_i represents the target memory trace being probed for recall while T_j represents the alternate memory that was learned with the i target memory in initial learning. The $S(C,T_j)$ term represents the strength of association between the cue and the alternate target and it is assumed that $S(C,T_j)$ is less than $S(C,T_i)$. Thus, the strength of the association between the cue and the correct target memory trace ($S(C,T_i)$) is represented by the baseline learning parameter, B (i.e., $S(C,T_i) =$ B). The strength of association between the cue and the alternate memory trace is represented by the other learning parameter, O (i.e., $S(C,T_j) =$ O), with B being assumed to be greater than O.

Likewise, the probability of recovery of the correct target memory in the indirect route is the ratio of the strength of association between the alternate memory trace (T_j) and the correct target recovery (R_i) to the sample space of possible memory trace samples for the alternate memory trace (i.e.,SS_R, see Equation 9 and Table 9).

$$p(recover_i \mid sample_j) = \left(\frac{S(T_j,R_i)}{S(T_j,R_i) + S(T_j,R_j) + 1}\right) \qquad \text{Equation 9}$$

Where T_j is the memory trace for the j memory that is not being probed for recall, R_i represents the recovery for the target memory being probed for recall and R_j represents the alternate memory recovery that was learned with the i target memory in initial learning. The $S(T_j,R_i)$ term represents the strength of association between the alternate memory trace to the correct target recovery (i.e., the association between the memory trace for target j and the recovery for target i) and $S(T_j,R_j)$ is the strength of association between the alternate memory trace and its correct recovery (i.e., the association between the memory trace for target *j* and the recovery for target *j*). Given that a memory trace should have a stronger association for its respective recovery, it is expected that $S(T_j,R_j)$ is greater than $S(T_j,R_i)$.

Kmax is the maximum number of retrieval attempts made before the retrieval process is terminated (Raaijmakers & Shiffrin, 1981). Kmax is set to 3 because the experimental learning from Experiment 3 results in two targets per cue. Because there are multiple targets per cue this imposes upper bounds on the retrieval probabilities. Setting Kmax > 1 increases these upper bounds. Specifically, if Kmax equals 1, this constrains the model with upper bound predictions of .5 for the probability of recall when the O parameter value approaches the B parameter value. By increasing Kmax the upper bound also increases. As can be seen in Table 9, the probability of sampling and recovery in Experiment 3 involves the same parameter in both the denominator and the numerator which leads to an upper bound of 1.0 for any given prediction equation. However, each equation also includes both the B and O parameters in the denominator, resulting in an upper bound of 0.5 as other learning increases and the O parameter approaches the B parameter value. Kmax greater than 1 increases this upper bound with increased retrieval opportunities. For example, if Kmax is equal to 3 the upper bound for recall for the baseline items increases from 0.5 to 0.875 (i.e., p(recall) = $1-(1-(0.5)^3) = 0.875$), which allows more freedom in the data and more realistic predictions for baseline performance given the cues used for recall.

The final parameter to be discussed is the recall learning parameter, R, which represents the amount of learning due to retrieval practice. This parameter only affects the recovery strength for the practiced and non-practiced items. Because the retrieval practice is cued with an independent cue of the target, this leads to an increased sampling strength between the independent cue and target memory trace. This means that the final recall cue used in Experiment 3 will have no benefit of sampling due to this retrieval practice. Thus, the sampling strength for all items at final recall is assumed to be the same (see Table 9). However, the retrieval practice also leads to an increased association between the target memory trace and the correct recovery of that memory (i.e., $S(T_i,R_i) + R$). This leads to increased recovery strength for practiced items when the direct route of recall is used (i.e., for practiced items $p(recover_i|sampe_i) = (S(T,R_i)+R)/(S(T_i,R_i)+R+S(T,R_j)+1)$, see Table 9). Therefore, the parameter R will only be added to the practiced items memory trace association with its correct recovery and only affects the probability of recall when the direct route of retrieval is used.

Conversely, for the *non-practiced* items, the probability of recall decreases to the extent that the indirect route is utilized. The independent cue retrieval practice has no effect on the strength of association between the alternate memory trace and the practiced items recovery (i.e., $S(T_j,R_i)$ remains constant at O). Retrieval practice only affects the target memory trace for the practiced item and has no affect on the non-practiced memory trace. Because the direct route of retrieval for the non-practiced item relies on sampling the non-practiced target trace, retrieval practice has no affect on the direct route of retrieval for the non-practiced items. However, the indirect route of retrieval for the non-practiced item relies on sampling the practiced target trace, which has an increased association strength to the practiced recovery. This leads to a decreased probability of recovery for the non-practiced item as the sample space for recovery (SS_R) has increased by the parameter R (i.e., p(retrieval)= $S(T_i,R_i)/(S(T_i,R_i)+R+S(T_j,R_i)+1)$, see Table 9). In this manner the retrieval practice leads to a decrease in recall for non-practiced items compared to baseline items. Therefore, the non-practiced items are predicted to have a lower probability of recall compared to baseline items when the indirect route is used.

A prediction of neo-classic interference theory is that the practiced items will have increased recall accuracy while the non-practiced items will have recall impairment, relative to baseline items. For the *practiced* items the recovery strength between the practiced target memory trace and target recovery increases by the parameter R in the direct route of retrieval, which leads to cue-independent recall benefit. In the same way that recovery interference leads to cue-independent recall impairment, recovery practice should lead to cue-independent recall benefit. For the *non-practiced* items this leads to a decrease in recall when the indirect route of retrieval is used as the practiced competitor recovery has been strengthened by the parameter R and has increased SS_R.

However, to the extent that indirect route of retrieval is not used, recall impairment is not expected for non-practiced items relative to baseline items. The indirect route of retrieval is dependent upon initial learning in that the participant must learn the alternate recoveries for the respective memory traces. If the participant uses a direct *learning* route such that the target memory traces only have one learned recovery, there is no possibility of subsequently using an indirect route of retrieval. This leads to differential parameter predictions from the neo-classic interference theory for participants who learn alternate recoveries and those who do not. Because the direct route results in only the correct sampling and recovery processes being practiced, this should result in greater learning for the direct route associations. Thus, the participants who did not learn alternate recoveries at initial learning would be expected to have a stronger learned association between the cue and the correct memory trace than participant who used both a direct and indirect route of learning. Similarly, as the learning strength for sampling and recovery is assumed to be equivalent, this means that the recovery strength for the participants who only used a direct route of learning should be greater that the recovery strength for participants who used both direct and indirect learning routes.

Neo-classic interference theory predicts that the baseline learning parameter, B, should be greater for participants who do not learn alternate memory recoveries compared to participant who do learn alternate recoveries. Further, if an alternate recovery is not learned, the O parameter reduces to 0: Participants who use only the direct route of learning will have essentially no other learning while participants who used both the direct and indirect routes of learning will have some positive O parameter value. Lastly, recovery interference theory predicts that the greater B parameter in conjunction with the null O parameter for one-path learning participants will lead to a greater R parameter value for these participants relative to two-path learning participants. The recovery strength for participants who only use the direct route of learning is assumed to be greater than the recovery strength for participants who use both routes of learning. This leads to a prediction that one-path learning participants will have an increased probability of correct retrieval practice, and thus increased R, compared to two-path learning participants. In sum, the neo-classic interference theory predicts that (1) a near 0 value for the O parameter for participants who only use a direct route of learning compared to a positive O value for participants who use a direct and indirect route of learning; (2) the participants who only use a direct route of learning will have greater B and (3) R parameter values than participants who use both routes of learning.

One possible measure for assessing which participants learned alternate recoveries (i.e., used direct and indirect routes of learning) would be independent cue retrieval practice accuracy. As no alternate recovery learning results in the O parameter being close to 0, participants who learn no alternate recoveries will have no sampling or recovery interference from the other target word (i.e., p(sample) and recovery is (B/(B+1)) rather than B/(B+O+1)). This leads to the expectation that participants who have only used a direct route of learning will have greater independent cue recall accuracy than participants who used both routes of learning. Thus, if the indirect pathway is learned during the initial stage of the experiment, then this provides a competitor recovery during retrieval practice. This will lead to lower retrieval practice accuracy and retrieval practice accuracy may serve as a proxy measure for use of the indirect pathway.

The data from Experiment 3 may be split by independent cue recall accuracy in order to assess the parameter value differences between these groups of participants. The better performers (BP) on the independent cue recall are expected to represent those participants who only used a direct learning route and did not learn alternate recoveries. Conversely, the worse performers (WP) on the independent cue recall are expected to represent those participants who used both direct and indirect learning routes and learned alternate recoveries. As can be seen from the parameter values reported in Table 10, the parameter values confirmed this interpretation of the individual differences elaborated in the neo-classic interference theory. As expected, the participants who performed better on independent cue recall (the BP participants) had an O learning parameter near 0 ($O < 0.001$), indicating that no other or alternate memories were learned. Conversely, the participants who performed worse on independent cue recall (the WP participants) had a greater, positive O parameter value ($O = 1.76$), indicating that alternate recoveries were learned. The difference in baseline learning between the BP and WP participants was also predicted, and observed, in the initial baseline learning parameter, B, where the BP participants had a greater baseline learning parameter ($B = 1.32$) than the WP participants ($B = 0.49$). Lastly, the BP participants also had a greater benefit from independent cue retrieval practice as evidenced by the larger R parameter for the BP participants ($R = 5.25$) compared to the WP participants R parameter values ($R = 1.80$).

Parameter	Better Performers	Worse Performers
Baseline Learning (B)	1.32	0.49
Other Learning (O)	<0.001	1.76
Recall Learning (R)	5.25	1.80

Table 10. Parameter values for SAM-RI parameters for Experiment 3.

Thus, the parameter values indicate that participants who perform better on the independent cue recall task used only the direct route of learning and did not learn alternate recoveries in initial learning. Conversely, the participants who performed worse on the independent cue recall task appear to have learned alternate recoveries in initial learning. This pattern of parameter results demonstrates the ability of the model to transform data patterns into psychologically meaningful parameters that may relate to different retrieval strategies adopted by different individuals. Next, we extend the models capabilities to explain the broader retrieval induced forgetting literature.

Chapter 7: Search of Associative Memory with Recovery Interference (SAM-RI) Model and the Retrieval Induced Forgetting Paradigm

Model Overview for Retrieval Induced Forgetting

In the retrieval-induced forgetting (RIF) paradigm, the process of retrieval practice for some items paradoxically appears to cause forgetting of other items. The practiced items have a greater probability of subsequent recall, but other items associated with the retrieval cued during retrieval practice are more likely to be forgotten (Anderson, Bjork, & Bjork, 2000; Anderson, Bjork, & Bjork, 1994; Anderson & Spellman, 1995). For example, if "fruit-orange" and "fruit-tangerine" is initially learned, then "fruit-orange" was selectively retrieved, orange would be more likely to be recalled and tangerine would be less likely to be recalled compared to baseline words such as "drink-cola" where no drink words were selectively retrieved.

In extending the SAM-RI model to this retrieval induced forgetting (RIF) paradigm, it is identical to the SAM-RI model in the think/no-think (TNT) paradigm in terms of the theory and equations for recall (see Equations 1 and 2 and Tables 11 and 12), sampling (see Equation 3 and Tables 11 and 12), and recovery (see Equation 5 and Tables 11 and 12). The SAM-RI model may capture the retrieval induced forgetting (RIF) results in the same way that it models data from the think/no-think (TNT) paradigm. In the RIF paradigm participants learn a category cue and multiple target items associated with the cue. For the practiced category half of these target items receive retrieval practice, while the remaining half receive no retrieval practice. Thus, recovery interference may be learned during retrieval when a non-practiced target item is (mistakenly) sampled but then the alternate target memory is recovered instead. This process of automatically sampling a memory trace results in the formation of an alternative recovery, which will later compete with the correct recovery. Specifically, learning an alternate recovery would result in a greater sample space for the recovery (SS_R) process of the non-practiced items (see Table 12 and below section for further discussion of the model parameters and assumptions). This would result in the observed RIF results of decreased recall for the non-practiced items from the practiced category relative to all other items.

A four-parameter version of SAM-RI is needed to model the general retrieval induced forgetting paradigm. These parameters are (B) Baseline learning, (R) Recall learning, (O) Other learning, and (A) Association. All of these parameters have been used in the SAM-RI model in fitting the data of Experiment 1 and Experiment 3

Model Specifics for Retrieval Induced Forgetting

The cues used in the retrieval induced forgetting paradigm are semantically related to multiple targets. Thus, SAM-RI learning parameter for the RIF paradigm (B for Baseline learning) is a single parameter that encompasses pre-experimental learning as well as experimental learning (i.e., $S(C,T_i)$ = B and $S(T,R_i)$ = B). For example, in the RIF paradigm participants may learn 'fruit-orange' and 'fruit-tangerine'. Here 'fruit' is semantically related to the targets and is used to cue multiple targets (i.e., 'orange' and 'tangerine'). This multi-target cue usage in RIF requires modifications of SAM-RI parameter values, but should not substantially affect the model. Specifically, increasing the number of targets that are associated with a cue increases the sample space for sampling (SS_S) in response to that cue. This is manifest in the model as an increased denominator for the probability of sampling, meaning that the $S(C,T_j)$ term is a positive value.

All experimental targets receive the same experimental learning, resulting in the targets having the same association strength between the cue and the target ($S(C,T_i)$ = B for all targets). This results in the SS_S for original cue being the sum of the association between the cue and all learned targets plus 1 (i.e., $S(C,T_i)+\Sigma S(C,T_j)+1$). Because all targets have the sample sampling strength (i.e., $S(C,T_i)=S(C,T_j)$) the SS_S reduces to the number of items learned multiplied by the association strength between the cue and target, plus one. The probability of sampling a target memory in the retrieval induced forgetting paradigm is thus expressed in Equation 10.

$$p(sample_i) = \frac{S(C,T_i)}{n * S(C,T_i) + 1} \qquad \text{Equation 10}$$

Where n = the number of target items learned with the cue at initial learning. In terms of model parameters where B represented the strength of association between the original cue and target, this results in B/(nB+1) (see Table 11).

Similarly, this multi-target cue use in RIF affects SAM-RI affects the independent cue recall equations. In the RIF paradigms, the independent cues are also category level cues that are associated with multiple targets from the studied lists (Anderson, Green, & McCulloch, 2000; Anderson & Spellman, 1995; Camp, Pecher, & Schmidt, 2005; Saunders & MacLeod, 2006). This leads the SAM-RI prediction equations for independent cue recall to have the same constraint as the original cue recall on the SS_S. Following the preceding example, 'citrus' may be an independent cue for the fruit category as 'citrus' is related to both the target words of 'orange' and 'tangerine.' Thus, as there are multiple targets that are associated with the independent cue, the SS_S reflects that in the denominator such that $\Sigma S(C,T_j)$ increases as the number of items associated with the independent cue increase.

	p(sample)	P(recover)	p(retrieve)
Baseline (Nrp)	$(\frac{B}{nB+1})$	$(\frac{B}{B+1})$	$(\frac{B}{nB+1})(\frac{B}{B+1})$
Practiced (Rp+)	$(\frac{B+R}{(\frac{n}{2})(B+R)+(\frac{n}{2})(B+O)+1})$	$(\frac{B+R}{(B+R)+1})$	$(\frac{B+R}{(\frac{n}{2})(B+R)+(\frac{n}{2})(B+O)+1})(\frac{B+R}{(B+R)+1})$
Non-Practiced (Rp-)	$(\frac{B+O}{(\frac{n}{2})(B+R)+(\frac{n}{2})(B+O)+1})$	$(\frac{B}{(B+O)+1})$	$(\frac{B+O}{(\frac{n}{2})(B+R)+(\frac{n}{2})(B+O)+1})(\frac{B}{(B+O)+1})$

Table 11. Prediction equations for original cue recall in terms of SAM-RI model for the general retrieval induced forgetting paradigm

In general, the number of target words associated with the independent cue is determined by the number of target words that are pre-experimentally associated with the independent cue (Anderson, Green, & McCulloch, 2000; Anderson & Spellman, 1995; Camp, Pecher, & Schmidt, 2005; Saunders & MacLeod, 2006). For example, if cherry and radish are the only target words associated with red, then the number of target associations with the independent cue 'red' is two. This leads to the probability of sampling with the independent cue being expressed in the model parameters to be A/(nA+1), where n = the number of target items from the studied targets that are associated with the cue and A is the pre-experimental association parameter.

	p(sample)	p(recover)	p(retrieve)
Baseline (Nrp)	$(\frac{A}{nA+1})$	$(\frac{B}{B+1})$	$(\frac{A}{nA+1})(\frac{B}{B+1})$
Practiced (Rp+)	$(\frac{A}{nA+1})$	$(\frac{B+R}{(B+R)+1})$	$(\frac{A}{nA+1})(\frac{B+R}{(B+R)+1})$
Non-Practiced (Rp-)	$(\frac{A}{nA+1})$	$(\frac{B}{(B+O)+1})$	$(\frac{A}{nA+1})(\frac{B}{(B+O)+1})$

Table 12. Prediction equations for independent cue recall in terms of SAM-RI model for the general retrieval induced forgetting paradigm.

However, this assumption only holds when the independent cue is a category level cue that is associated with multiple targets in the study (i.e., 'citrus'). If the independent cue is an item level cue (i.e., if 'apple' is used to cue 'orange'), such as in the TNT paradigm, then this reverts to the same equations used by SAM-RI in the TNT paradigm. Specifically, as there are no competing targets in the study that are associated to the independent cue, the SS_S decreases as the $S(C,T_j)$ term is reduced to zero.

Another issue relating to the multi-target cue involves the sampling strength of items from the practiced category. For the items that receive practice, they increase in sampling and recovery strength by the value of the <u>R</u>etrieval practice parameter R (i.e., $S(C,T_i)$ = B+R and $S(T,R_i)$ = B+R). Conversely, for the items that don't receive practice from the practiced category, to the extent that these items are sampled and then recovered to the alternate completion of a practiced item, they increase in sampling strength by the <u>O</u>ther learning parameter, O (i.e., $S(C,T_i)$ = B+O while $S(T,R_i)$ = B). However, the recovery strength for these items is not incremented as the target memory is never recovered to its correct completion and is instead recovered to an alternate item.

This alters the sample space for sampling (SS_S) with original cue as the target memories associated with the original cue now have differing association strengths. The sum of the strength of association between the cue and the targets is split between half of the items receiving practice and half of the targets not being practiced. For the practiced items these having a stronger strength of association between the cue and target than the other non-practiced items. More specifically, this sum is equal to the addition of half of the targets baseline (B) learning plus their retrieval (R) learning, plus the addition of half of the targets baseline (B) learning to their other (O) incidental sampling increase (i.e., $S(C,T_i) + \Sigma S(C,T_j) = (n)*(S(C,T_i)) =$ (n/2)*(B+R) + (n/2)*(B+O), where n = the number of items studied with that cue, see Table 11).

Lastly, the forgetting observed in the RIF paradigm is a result of selective retrieval of some items rather than the active suppression of items as in the TNT paradigm. This difference has little impact on the SAM-RI models equations and predictions as the model never assumed participants were explicitly trying to suppress items in the TNT paradigm. In the RIF paradigm recovery interference occurs for items from the practiced category that do not receive retrieval practice. To the extent that the non-practiced items are inadvertently sampled but the practiced target is recovered, this will result in recovery interference. Hence, in both the TNT and RIF paradigms, the Other learning parameter is used to capture this other recovery learning. The sample space for recovery (SS_R) is incremented by this parameter for the non-retrieved items in the practiced category (i.e., $S(T,R_j)$ = O for non-retrieved items and $S(T,R_j)$ = 0 for retrieved and baseline items, see Table 11).

Thus, recovery interference results from a person learning alternate recoveries during retrieval when a non-recall target item is automatically sampled but then the alternate target memory is recovered. The automatically sampled memories then have an alternate recovery that competes with the correct recovery when recall is later attempted for that item. This results in the generally observed RIF results of decreased recall for the non-practiced items relative to all other items. In particular, learning the alternate recovery results in a greater sample space for the recovery process of the non-practiced items (see Tables 11 and 12). The retrieval practice also leads to an increase in recovery strength for practiced items which leads to an expectation of cue-independent recall benefit for these items relative to baseline. In this manner the neo-classic interference theory captures the traditionally retrieval induced forgetting results.

Chapter 8: Search of Associative Memory with Recovery Interference (SAM-RI) Model, Empirical Findings from the Retrieval Induced Forgetting Paradigm, and a Neural Network Model

The SAM-RI model captures the general findings from the think/no-think and retrieval induced forgetting paradigms. However, Norman, Newman and Detre (2007) have already specified a neural network model of retrieval induced forgetting that explains many nuances found in the RIF literature. Thus, the SAM-RI model is further specified to demonstrate that it can explain all of the RIF results that the Norman, Newman and Detre (2007) model encapsulated. For each of the phenomenon that the Norman model demonstrates, the SAM-RI is also able to explain these results. In the subsequent section the theoretical predictions from the SAM-RI model are laid out to address each of the Norman modeling features and the corresponding SAM-RI model instantiation is outlined for each of these theoretical predictions (see Tables 11 and 12).

First, Norman, Newman, and Detre (2007) address the cue-independent forgetting nature of RIF memory impairment (Anderson & Spellman, 1995). Cue-independent forgetting has already been discussed and detailed in the SAM-RI model, both for the think/no-think paradigm as well as the retrieval induced forgetting paradigm (see Table 12 and above section for a more detailed discussion). In the

SAM-RI model this is instantiated by the O parameter. The other learned parameter, O, is added to the target sampling strength as well as the sampling and recovery sample space, resulting in an increase in sampling strength but a decreased probability of recovery (i.e., p(retrieve of Npr items) = [(B+O)/(B+O+nB+1)]*[(B/(B+O+1)], see Tables 11 and 12).

A second empirical retrieval induced forgetting result addressed by Norman, Newman, and Detre (2007) was the finding that retrieval induced forgetting may be observed with novel episodic associations as opposed to pre-existing semantic associations (Anderson & Bell, 2001). This is similar to the think/no-think paradigm where the word pairs learned are not pre-experimentally associated. As the SAM-RI model has already been specified in the TNT paradigm where forgetting occurs for items that are not pre-existing semantic associates, the model already encompasses this RIF effect. In the model instantiation, the learning parameter in retrieval induced forgetting paradigms, B, is assumed to encompass both experimental and pre-experimental learning. However, in the think/no-think paradigm the learning parameter is assumed to only reflect experimental learning (which is the case in the Anderson and Bell (2001) study). Thus, this is an instance where the SAM-RI model for retrieval induced forgetting assumes that the learning parameter, B, only reflects experimental learning. This leads to the prediction that the B parameter value in these cases is less than the B parameter value when it includes both types of learning (pre-experimental and experimental).

A third retrieval induced forgetting phenomenon that Norman, Newman and Detre (2007) address is the finding that retrieval induced forgetting is dependent upon selective retrieval practice. Anderson, Bjork, and Bjork (2000) assessed forgetting with the traditional selective retrieval practice compared to extra study (i.e., 'fruit – orange' was presented rather than 'fruit – or____') and reversed practiced (i.e., 'fr___ - orange was practiced rather than 'fruit – or____'). Forgetting of competitors was only found for those items belonging to the selective retrieval practice groups (i.e., 'banana' showed impaired recall only when 'fruit – or___' was practiced and banana was not retrieved).

Again, the SAM-RI model captures this finding with no modifications to the model needed. Extra study does not result in interference as it does not encourage or induce a person to use the 'indirect' route of learning which produces multiple recoveries for a memory trace. In order to learn an alternate recovery *recall* practice is needed. Simply viewing the items will not lead learning alternate recoveries, as there is no need for sampling and recovery when the fully recovered word is presented for *study*. In the SAM-RI model this is instantiated by having only the recalled items receiving the addition of the R parameter to sampling and recovery strength (i.e., B+R in the numerator and denominator for sampling and recovery) whereas the study items would not receive any additional R increases in sampling or recovery. Though participants might get a small increase in sampling and recovering from study, the Anderson, Bjork, & Bjork (2000) results indicate that this increase is not significant. Thus, it does not appear necessary to include an additional parameter for 'study learning' as the results can be explained by having the studied items maintain the same predicted results as the baseline items (i.e., p(retrieval of studied and baseline items) = [(B/(B+nB+1))*(B/(B+0+1)), see Table 11]. Lastly, the non-practiced items from the practiced category receive sampling strengthening with the addition of the O parameter along with recovery 'weakening' by adding the O parameter to the SS_R (see Table 11). This results in the expectation that (1) the studied items and the baseline items having equivalent recall accuracy predictions; (2) retrieval practice items having an increase recall accuracy prediction relative to baseline; and non-practiced items from the retrieval practice category having a decreased recall accuracy prediction relative to baseline. These expectations are what is found in the RIF literature (Anderson, Bjork, & Bjork, 2000).

A fourth retrieval induced forgetting phenomenon that Norman, Newman and Detre (2007) address is the finding that forgetting occurs for semantically strong competitors but not semantically weak competitors (Anderson, Bjork, & Bkork, 1994). The SAM-RI model already predicts this differential forgetting for strong and weak competitors as the model has an assumption of a non-monotonic relationship between memory strength and recovery interference. The stronger competitors (i.e., the memory has a strong semantic association with the cue or is a strong exemplar of the category) are more likely to be automatically sampled but are also more resistant to interference when an alternate recovery is learned. Conversely, weaker memories are less likely to be automatically sampled, but are more affected by interference when an alternate recovery is learned. As is evident, forgetting is a delicate balancing of memory strength. The Anderson, Bjork, and Bjork (1994) finding demonstrates this point as the weak competitors did not show RIF because they were not strong enough to produce automatic sampling. Conversely, the strong memories did show RIF because they were at the right strength to both produce automatic sampling and allow for interference.

In order to model these non-parametric predictions in SAM-RI, the learning parameter, B, and the other learning parameter, O, are altered. The baseline learning parameter (B) is set such that every item had the same initial learning strength that subsumes both pre-experimental and experimental learning. However, in order to model this differential strength effect the model instantiates two learning parameters rather than one baseline learning, similar to what was done in modeling the TNT paradigm memory strength manipulation with W (for 'weak' memories) and S (for 'strong memories').

Further, for items that experience automatic sampling (i.e., medium to strong memories) that results in multiple recovery associations, these items have an increased probability of correct sampling and a decreased probability of correct recovery. The other learning parameter, O, is added to the sampling strength and the SS_S and SS_R for these items. These strong items then have an expectation of decreased recall accuracy compared to baseline. Similarly, given the assumption that weak memories are likely not be automatically sampled, the O parameter may not be applied to these items, leaving these items with a prediction of recall accuracy equivalent to baseline items, which would demonstrate no RIF for weak items.

As can be inferred, the larger the initial learning parameter for stronger items, the less impact the O parameter has on the items recall probability. The O parameter also has a fairly small value, reflecting the relative low rate of participants using this 'indirect route' of learning an alternate recovery. Thus, to the extent that initial learning is strong, the O parameter has little effect on the probability of recall for strong items, demonstrating no RIF. This shows the non-monotonic relationship between strength of an item and RIF whereby items of mid-level strength are affected by recovery interference, but very weak and very strong items are not.

Additionally, this leads into another RIF nuance that Norman, Newman, and Detre (2007) address: Increasing the strength of one competitor relative to another competitor reduces retrieval induced forgetting for the second competitor. This is captured with the SAM-RI model in that increasing the association between one target to the cue results in increased probability of that cue being automatically sampled, and a simultaneous decrease in the competitor being sampled.

A fifth empirical retrieval induced forgetting result addressed by Norman, Newman, and Detre (2007) was the finding that semantic generation of non-studied category exemplars leads to forgetting of previously studied exemplars from those categories (Bauml, 2002). As the RIF paradigm uses multi-target cues (i.e., category cues) to cue retrieval practice then other, non-experimentally studied items that are related to the cue may be automatically sampled during retrieval practice. These non-experimental items that are sampled during retrieval have an association with the alternate recovery of the specific target being practiced with retrieval, resulting in subsequent recovery interference. It doesn't matter if the item was studied experimentally, if the item is related[4] to the presented cue it has a probability of being automatically sampled and thus having multiple learned recoveries.

This is instantiated in the interference model with non-experimentally studied semantic associates tested at final recall having a similar prediction equation to the

[4] In order for a non-experimentally learned associate to be automatically sampled, the item likely has to be a fairly strong semantic associate

non-practiced items from the practiced category. The non-experimentally studied associates have the O parameter added to their sampling strength as well as to their sampling and recovery sample space. The Bauml (2002) results indicate that the non-studied semantic associates have similar impairment to studied items that were not practiced so there does not appear to be a need for another parameter as O suffices for both item groups. However, it is possible to create a parameter to indicate Greater Other learning for items studied in the experiment and a parameter to indicate Lesser Other learning for semantic associates of the items that were not in the original study. Similarly, the strength of association between the non-experimentally studied exemplars and the cue would reflect only pre-experimental learning (with the addition of O in the sampling strength) and so would have a strength of association of the parameter A, reflecting the pre-experimental association. However, this is another simplifying assumption, it may be the case that non-experimental associates to the cue have a lesser or greater association strength than experimental associates. If the data indicate this simplifying assumption is inadequate, an alternate parameter may be used to indicate that the pre-experimental association between the non-studied items and the studied items differs.

This also addresses a sixth empirical finding addressed by Norman, Newman, and Detre (2007) that practicing retrieval of studied word pairs leads to subsequent cue-independent forgetting of non-studied semantic associates (Carter, 2004). As the preceding section illustrates, recovery interference is not limited to studied items and non-experimentally learned items may be affected by recovery interference as a result of selective retrieval practice with a cue that is semantically associated to the non-studied item. As recovery interference occurs between the memory trace and the recoveries associated with that memory trace, this interference is cue-independent. The SAM-RI model, thus, allows for non-studied items that are semantically associated with the retrieval practice cue may to suffer recall impairment as observed by Cater (2004).

A seventh empirical retrieval induced forgetting result addressed by Norman, Newman, and Detre (2007) was the finding that not all independent cues show recall impairment in the retrieval induced forgetting paradigm, even though original cue recall shows impairment (Perfect et al., 2004). In general, when original cue recall impairment is observed in the absence of independent cue recall impairment (as was the case in Experiment 2), it is assumed that sampling interference but not recovery interference was produced as a result of the experimental manipulation(s).

However, the Perfect et al. (2004) study used a unique version of the retrieval induced forgetting paradigm that may have resulted in cue-dependent forgetting for a very different reason. Rather than the standard retrieval induced forgetting paradigm that relies on semantic associations for independent cues, Perfect et al. (2004) used an unrelated photograph that was only associated with the target word through experimental learning. During the initial learning phase of the study participants viewed a unique, unrelated, photo along with each word. This photo was subsequently used as the independent cue at the conclusion of the study and the non-practiced items were recalled with similar accuracy as the practiced items with this cue. This novel finding may indicate that the SAM-RI model deals primarily with semantic memory rather than episodic memory and this issue should be delved into in future studies.

Lastly, Norman, Newman and Detre (2007) manipulated retrieval practice success by varying the semantic strength of the target items (i.e., the association of the target to the cue). Their model found that "optimal strengthening occurs in conditions where the target just barely wins at practice (i.e., recall accuracy at practice is high and competition is also high)." This finding also makes sense in the neo-classic interference theory in that a target is most 'strengthened' when it 'just barely wins at practice.' In this case the target item wins by being correctly recalled and is strengthened (as represented by the parameter R). But if the competing target item is a strong competitor it is likely that this competitor is automatically sampled on some trails and then recovered to the target memory, resulting in recovery interference (as represented by the parameter O). The target memory is, therefore, strengthened while the competitor is 'weakened' by recovery interference. To the extent that the competitor is not strong enough to be sampled the practiced target memory is still strengthened, but the competitor is not 'weakened' which lessens the recall discrepancy between these items. The 'optimal' strengthening of the practiced target, therefore, occurs when the target is strengthened with successful recall while the competitor is simultaneously 'weakened' with recovery interference. If there a practiced item is so strong as to not suffer from any competition during retrieval practice, it is likely that the competitor is never sampled as the target is so easily recalled.

Thus, the SAM-RI model has been specified theoretically and mathematically to capture the results observed from the retrieval induced forgetting paradigm.

Furthermore, the model has explained and specified the many empirical findings in the retrieval induced forgetting literature that the Norman, Newman, and Detre (2007) model of RIF captured. Further, the SAM-RI model has modeled and fit data from the think/no-think paradigm (Experiment 1) and a modified retrieval induced forgetting paradigm (Experiment 3) as well as specifying a myriad of empirical results from the broader retrieval induced forgetting literature. Future directions may involve the model being used to fit observed data in a more traditional version of the retrieval induced forgetting paradigm[5], while further testing predictions from the model. The SAM-RI model appears to be a well-specified model of interference effects that has explanatory power across the standard 'inhibition' paradigms.

[5] A literature review of the retrieval induced forgetting literature provided no ideal empirical results to model with SAM-RI for a myriad of reason, but primarily there were too few data points reported as only one study used *both* original and independent cue recall.

Chapter 9: General Discussion

Behavioral Studies Summary

The inhibition theory of forgetting memories currently claims dominance over interference theory due to the apparent inability of interference theory to explain independent cue recall results. However, the studies reported in this paper, along with the SAM-RI model, suggest that interference theory is not at odds with the cue-independent forgetting. Global memory models assume that recall is composed of two stages: sampling of a partial memory and recovery of the memory. By extending interference into the second stage of recall, recovery, interference theories of forgetting are able to explain the extant data and make predictions.

Experiment 1 provided support for the neo-classic interference theory by testing three predictions that flow from the theory. Critically, neo-classic interference theory expects that performing any other memory recovery in response to a partially retrieved memory should impair later recall. This prediction was confirmed by including a press-enter condition in the traditional think/no-think paradigm, which produced recall impairment that was similar to the observed recall impairment for the no-think items.

The neo-classic interference theory also predicts that strong memories (operationalized as memories recalled correctly three times) are less susceptible to recovery interference than weaker memories (operationalized as memories correctly recalled once). Weak memories showed less original cue recall impairment after suppression training than strong memories both original cue and independent cue recall in Experiment 1. Lastly, as recognition does not require recovery processes it should bypass any recovery interference. This leads to an expectation from neo-classic interference theory of no impairment for suppressed items (i.e., no-think and press-enter items) relative to baseline items when tested with recognition rather than recall. This recognition prediction was also confirmed in Experiment 1.

Furthermore, Experiment 2 aimed to empirically assess the assumption that low-frequency words have low initial recovery strength by manipulating the frequency (low or high) of target words. From an interference viewpoint, Experiment 2 demonstrated sampling, but not recovery, interference in recall. This is shown in the recall impairment for the original cue recall of suppression items relative to baseline items, but no recall impairment for these items with independent cue recall. As independent cue recall is viewed as a direct test of recovery interference, any independent cue forgetting effects are assumed to be due to recovery interference. Failure to observe forgetting demonstrates suppression training did not produce recovery interference, which was the case in Experiment 2.

However, there was recall impairment in Experiment 2 with original cue recall, which includes the potential for both sampling and recovery interference. Given that the independent cue recall results indicate no recovery interference due to suppression training, it may be assumed that the observed recall impairment for the original cue recall resulted from sampling interference alone. Learning alternative responses such as ‘not thinking’ and pressing the enter key in response to the original cue, lead to competition between the originally learned target memory and the newly learned response. This competition resulted in subsequent recall impairment for original cue. Put another way, participants used the direct route of associating the cue with the new response and did not use the more indirect route; they did not automatically sample the original target in response to the original cue in suppression training.

Additionally, because the independent cue results demonstrate that there was no recovery interference due to suppression training in Experiment 2, the differential effects of recovery interference on word frequency could not be assessed within this experiment. Thus, the results from Experiment 2 emphasize that recovery interference may be a small effect as it is often hard to observe and replicate cue-independent forgetting (Bulevich, Roediger, Balota, & Butler, 2006).

Experiment 3 used a novel paradigm modified from the retrieval induced forgetting paradigm to further test predictions from the neo-classic interference theory. This experiment was designed to assess whether recovery strengthening of a subset of associated items (practiced items) impaired recall of the other associated items (non-practiced items). The neo-classic interference account predicted better recall for items receiving retrieval practice and recall impairment for those items that were paired with an item receiving retrieval practice compared to baseline words where neither target word received additional retrieval practice. The results from Experiment 3 showed the benefit of retrieval practice of items on subsequent recall, however, the difference between baseline and non-practiced words recall was dependent upon how successful the participant was at the retrieval practice. Those participants who were successful with the retrieval practice (i.e., had a retrieval practice accuracy of above 90%) showed no interference effects, as there was no difference between baseline and non-practiced words. Conversely, the participants who were not as successful with the retrieval practice (i.e., who had retrieval practice accuracy of 90% or less), showed interference effects as exemplified by non-practiced items being recalled significantly less than baseline items (see Table 4).

While it may at first appear to contradict interference theory that people who did most of the retrieval practice correctly, and thus had greater recovery strengthening of items, showed no interference effects. This it may be thought of as a ceiling effect where individual differences played a large role. If a participant only uses a direct route of learning and does not learn alternate recoveries, this leads to an increased probability of independent cue and final cue recall due to no interference from the other learning (i.e., the O parameter is 0 for these participants). If the participants who are able to easily recall items during retrieval practice are more likely to use the direct route of retrieval and never sample the alternate memory trace, there will be no interference effects. People who have a looser association space will use the indirect pathway more (they sample the wrong trace), which produces worse performance during retrieval practice. This issue was more fully addressed with the modeling of Experiment using the SAM-RI model where the parameter values for the observed results support the idea that participants who perform better at independent cue recall have not learned any alternate recoveries. This lack of learning alternate recoveries leads to increased independent cue and final cue recall accuracy, as there is little interference at sampling or recovery.

A major benefit of Experiment 3 is in the creation and use of a novel paradigm that may offer many new insights into the underlying mechanisms of forgetting. The Experiment 3 paradigm is a modified retrieval-induced forgetting paradigm that may be used to experimentally assess the recovery process as final recall differences are assumed to be uniquely attributable to a change in the recovery process considering that retrieval practice was achieved via an independent cue.

Neo-Classic Interference Model of Forgetting (SAM-RI)

Beyond the behavioral data, the search of associative memory with recovery interference (SAM-RI) model has been specified theoretically and mathematically to capture the results observed from both the think/no-think and retrieval induced forgetting paradigms. The SAM-RI model used 6 free parameters to model the 24 observed average accuracy results from Experiment 1. The model fit was remarkably close to the observed data (see Table 8), and though the fit was technically rejected, this may be due more to the large sample size rather than the model not fitting well, though further studies would be warranted.

An important constraint on the neo-classic interference model involves the non-monotonic relationship between memory strength and recovery interference. In the recovery interference account of cue-independent forgetting, a memory suffers interference when the target memory is (mistakenly) sampled during suppression training or selective retrieval. This automatic sampling occurs to the extent that the initial memory is strong enough to promote automatic sampling, regardless of instructions. In modeling the results from Experiment 1 and specifying the general model for retrieval induced forgetting, a fixed degree of automatic sampling is assumed. This simplifying assumption was sufficient for the current modeling, but in general this assumption is likely to be false. If a memory is too weak it will fail to produce automatic sampling and will, therefore, have no recovery interference. Conversely, if a memory is too strong it will be automatically sampled but will not suffer impairment as the newly learned recovery offers little competition for the strong memory. Cue-independent forgetting in the SAM-RI model is, therefore, a delicate balancing act that requires memories of moderate strength so as to promote automatic sampling while still allowing for the detrimental effects of learned avoidance.

The SAM-RI model was also specified for the modified retrieval induced forgetting paradigm used in Experiment 3. Though the model perfectly fit the behavioral data from Experiment 3, this was expected, as there are an equal number of free parameters as data points that were fit. The more interesting aspect of the modeling from Experiment 3 was the parameter values from the model. Neo-classic interference theory makes predictions regarding relative parameter values. As predicted, the parameter values indicated that participants who performed better on the independent cue retrieval practice, appear to only use the direct route of learning and did not learn alternate recoveries (as evidenced by the O parameter being near 0). Conversely, the participants who performed worse on the independent cue retrieval practice appear to have learned alternate recoveries in initial learning. This difference in initial learning results in greater baseline learning (B parameter values) and independent cue recall benefit (R parameter values) for participants who do not learn alternate recoveries compared to participants who did learn alternate recoveries. This pattern of parameter results confirmed all of the neo-classic interference theory predictions.

One issue that will need to be addressed in subsequent research is why some participants learn alternate recoveries in this paradigm while others do not. This may be an experimental issue or an individual difference issues, or some combination of both. Given that the direct route of learning is the more efficient and accurate method of learning, as it reduces possible interference and results in increasing the strength of association between the appropriate memory traces and recoveries, it is likely that participants who only used a direct route of learning in initial learning have better memory capacity or memory strategies.

The SAM-RI model has thus been able to model think/no-think results in Experiment 1 as well as the modified retrieval induced forgetting paradigm results from Experiment 3. The model is also able to easily explain and specify the many empirical findings in the retrieval induced forgetting literature. The SAM-RI model was easily extended to the many RIF findings reported in the Norman, Newman, and Detre (2007) model, as it needed little change in the model equations, parameters and no serious theoretical extensions were required. Thus, the SAM-RI model has modeled and fit data from the think/no-think paradigm as well as specifying a myriad of empirical results from the retrieval induced forgetting literature. Future directions may involve the model being used to fit observed data in the retrieval induced forgetting paradigm and testing predictions from the model.

A General Theory of Forgetting

Because inhibition easily accounts for cue-independent forgetting and classic interference theory is unable to account for such forgetting, this has been taken as evidence that cue-independent forgetting is a unique marker of active memory inhibition. Thus, a wide variety of results have, therefore, been interpreted in terms of inhibition theory rather than interference theory. Inhibition theory has lead to new paradigms for studying forgetting (Anderson & Bell, 2001; Anderson, Bjork, & Bjork, 1994, 2000; Anderson, Green, & McCulloch, 2000; Anderson & McCulloch, 1999; Bjork & Bjork, 2003; Conway et al., 2000; Johnson & Anderson, 2004: Veling,& Van Knippenberg, 2004) and has been applied to the interpretation of neuroimaging results of forgetting in the think/no-think paradigm (Anderson, 2006; Anderson, Ochsner, Kuhl, Cooper, Robertson, Gabrieli, Glover, & Gabrieli, 2004; Conway & Fthenkai, 2003; Depue, Banich & Curran, 2006). There have even been applications of inhibition theory to fields outside of psychology, such as linguistics (Levy, McVeigh, Marful, & Anderson, 2007). Inhibition theory clearly has impacted a wide range of research areas.

However, the findings taken as evidence for inhibition theory can be interpreted within the context of interference. For example, Anderson et al. (2004) presented neuroimaging data as evidence for inhibition theory as it was not easily accounted for by interference theory. Participants performed the think/no-think task and had their brains scanned using magnetic resonance imaging (MRI) during suppression training. Consistent with previous research (Anderson & Green, 2001), the behavioral data showed a decreased probability of final recall for the no-think items compared to the think items. Brain imaging during the suppression learning showed reduced hippocampal activation and increased prefrontal activation for the no-think items compared to the recall items. Anderson et al. (2004) argue that this confirms inhibition theory: the increased prefrontal activation shows recruitment of executive control processes that inhibit the hippocampus to prevent declarative recollection as shown by the decreased hippocampal activation. However, this pattern of activation is also consistent with an interference account. For example, increased activation in the pre-frontal region would be expected if the participant was attempting to learn an alternative recovery – an effortful and attentionally demanding process. Additionally, decreases in activation in the hippocampus would be expected if the participant was following instructions to not retrieve the target memory and therefore was not accessing the hippocampal representation. Thus, one does not need to postulate active inhibition of the hippocampus by the prefrontal cortex to obtain the observed pattern of results: increased activation in the prefrontal region may result from the use of executive resources to form a new recovery and simultaneous failure to access the target memory. Any subsequent memory deficit for the target memory may be due to the competition between the newly learned recovery and the previously learned recovery.

A further empirical result that may be explained in terms of the neo-classic interference theory comes from a recent study that looked at the-tongue (TOT) phenomenon. Warriner and Humphreys (2008) presented participants with definitions and had participants attempt to provide the correct word for the definition. Participants could respond with the correct word, an incorrect word, or report being in a TOT state (ex. I think I know this word and I am sure I can eventually recall it). The correct word was eventually provided to all participants, but the length of time a participant was allowed to remain in the TOT state was manipulated. They found that the longer a person remained in a TOT state in response to the definition, the more likely that person was to re-enter the TOT state when subsequently presented with the same definition. One interpretation of this result is that participants were able to successfully sample the partial memory, but were unsuccessful at recovering the memory. The prolonged TOT state after recovery failure may have induced participants to recover the partial memory to a TOT state rather than the correct full recovery. Thus, it appears that the participants learned to forget through learning an alternate recovery.

However, there is one finding in the memory literature that appears to contradict the recovery interference account. Anderson and Green (2001) included a "no-say" condition in the think/no-think paradigm that did not show recall impairment. The "no-say" condition instructed people to think of the target word but not say the word aloud or type the word. After suppression learning with the "no-say" instructions, participants showed no decrement in final recall. This result may appear at first blush to be inconsistent with recovery interference theory; however, recovery interference theory is compatible with the observed data. The "no-say" results emphasize that the alternate learning is in response to a partial memory and solely tied to the overt response. If participants successfully followed the no-say instructions and covertly retrieved the target memory but withheld any overt response, no new alternative recovery to the sampled memory is being learned and thus no forgetting would be predicted by the recovery interference theory.

Furthermore, the behavioral data and the successful application of the SAM-RI model provide support for the neo-classic interference theory, but this does not necessarily falsify inhibition theory. Indeed, certain inhibition accounts may be compatible with these results. The purpose of the research reported in this paper is to provide an empirically and mathematically viable interference theory that can capture cue-independent forgetting, as the neo-classic interference theory does. This theory provides a theory of forgetting that is parsimonious with the rich and successful history of interference theories of forgetting while explaining cue-independent forgetting theoretically and mathematically with the SAM-RI model. Therefore, it is no longer appropriate to *assume* that forgetting in these paradigms is necessarily due to inhibition as interference theory is now a credible alternative. In conclusion, these results and the success of the SAM-RI model in the think/no-think and retrieval induced forgetting paradigms offer a viable theory of interference causing cue-independent forgetting. This will hopefully provide a caution for accepting inhibition as the only theory to explain the extant data and may lead the way for models and explanations of results (such as neuropsychological interpretations) based on interference theory.

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