E ERP CORRELATES OF FORGETTING: AN INVESTIGATION OF RESOURCE ALLOCATION AS A POTENTIAL NEURAL MECHANISM BEHIND RETRIEVAL-INDUCED FORGETTING

Marie Walters

A Thesis Submitted for the Degree of MPhil
at the
University of St. Andrews

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MPhil Dissertation by Marie Walters

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ABSTRACT

The present study was aimed at investigating a potential mechanism behind retrieval-induced forgetting that we have termed resource allocation. Three experiments were designed around the notion that increasing the number memories associated with one concept may reduce retrieval-induced forgetting by spreading out the limited resources available for that concept. In two experiments, we expanded the standard retrieval-induced forgetting (RIF) paradigm by increasing the number of items in each category and varying the amount of Rp+ and Rp- items. In one of these experiments, we recorded event-related potentials (ERPs) to examine the electrophysiological correlates of retrieval-induced forgetting. We then compared these findings to a standard version of the RIF paradigm as a control experiment. All three experiments produced significant facilitation effects, but failed to produce retrieval-induced forgetting. The absence of RIF in the present study, however, when combined with the imaging data allows us to discern the ERP correlates of selective retrieval from those of retrieval-induced forgetting. In the discussion, we present our case against conclusions drawn in other studies about the ERP correlates of RIF, and suggest that the characteristic frontoparietal components often found in RIF studies reflect the neural correlates of selective retrieval rather than inhibition.

I, Marie Walters, hereby certify that this thesis, which is approximately 16,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student in September, 2009 and as a candidate for the degree of MPhil in Neuroscience in September, 2009; the higher study for which this is a record was carried out in the University of St. Andrews between 2009 and 2010.

Date: 1st of September, 2010 Signature of candidate: Marie Walters

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of MPhil in Neuroscience in the University of St Andrews and that the candidate is qualified to submit this thesis in application for that degree.

Date: 1st of September, 2010 Signature of supervisor Malcolm MacLeod

Signature of supervisor Ines Jentzsch

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Contents

INTRODUCTION

Why do we forget?

Twelve years ago, a computer engineer named Gordon Bell began to digitalize his experiences. Today, Bell wears a special camera on his head that allows him to wirelessly archive visual and audio information every day of his life. Computer systems in his home record every phone call, save every internet search, and even monitor the movements of his mouse and keyboard. In one year alone, Bell recorded 25,000 megabytes of information through reading text, hearing music, watching movies, and otherwise documenting his life (Bell & Gemmell, 2007). Despite this vast amount of perceptual information that we are able to sense, researchers estimate that humans are only capable of storing a few hundred megabytes over a *lifetime* (Landauer, 1986). Where does all of the information go?

Much of the information that we perceive may never be processed and converted by our brains into a construct that can be stored and later recalled. This process of memory encoding often fails us when we are distracted, interrupted, or not selectively attentive. A second type of forgetting may occur when one's brain does not consolidate a representation into long-term memory. This type of memory impairment happens to all of us everyday, and for some of the same reasons that our brain fails to encode (e.g. deficient attention/ effort).

In these aspects of memory encoding and storage, Gordon Bell's computer systems have seemingly advanced the capabilities of human memory. However, there is a third part to human memory that even Microsoft's skilled computer scientists have yet to replicate. Currently research teams are designing artificial intelligence that can organize and strategically search the tremendous amount of data that Bell accumulates daily. Extracting particular knowledge from this gigantic store of information is the most challenging aspect of Microsoft's project, yet our brains have already evolved sophisticated systems for retrieving specific memories on demand. This built-in ability to manage and selectively recall memories brings us to the purpose of this study and to the final step of memory processes: memory retrieval.

If a memory is there, why can we not retrieve it?

Memories that we encode and consolidate in long-term storage may still be inaccessible at times for a variety of reasons. The literature concerning memory retrieval often groups these reasons by the brain mechanisms that underlie each circumstance. One of these divisions is between passive and active forgetting. Passive forgetting occurs indirectly and nonspecifically and can be caused by damage to the strengths of connections through the passage of time, aging, trauma, or disease. In addition to physically weakening neural connections, forgetting may occur because the contextual cues present at the time of encoding are no longer present at the time of retrieval. This contextual drift can be caused by the passage of time and also by the integration of new information which updates or maintains a context cue (Morris & Gruneberg, 1994).

Another type of passive forgetting occurs when you cannot remember the name of something, but you know the first letter of the word you are trying to remember. This forgotten item could be a person you've known for years, or the name of the shop where you bought your coffee this morning. Eventually, the memory will return to you, or be represented to you, and you will recognize it immediately because the item already exists in your memory. You were unable to retrieve the memory because the cue that you were using to recall the memory was not specific enough (e.g. "Her name starts with an 'S'"). Evidence from several studies suggests that this "tip-of-the-tongue experience" occurs when the combined information sources required to recall the target memory do not have sufficient activation to reach a threshold for retrieval (Brown, 1991).

An alternative hypothesis would be that the intrusion of another related memory is blocking the target memory.   While it may not account for tip-of-the-tongue experiences, this concept of blocking or interference is common in the psychological literature on active forgetting. Interference is built on the notion that our memories are highly intertwined; a memory of a meal might also bring to memory a conversation, a person, and a place. This interconnectedness is useful for organizing and locating related memories. However, it also increases the number of target memories (e.g. conversation, person, place) associated with a cue (e.g. one meal), and hence reduces the likelihood that we will be able to retrieve that target memory (Morris & Gruneberg, 1994).

Robert Bjork characterizes blocking as just one form of active forgetting or "retrieval inhibition". To be classified as retrieval inhibition, there must be a mechanism that causes an old memory to become non-retrievable (because of a new memory), non-interfering in the recall of the new memory, and yet still in memory, recognizable, and relearnable (Bjork, 1989). Bjork differentiates the retrieval inhibition/blocking described above from retrieval inhibition/ suppression. He describes the former as a "by-product" of activating other memories, whereas with the latter, inhibition is directed at the inhibited memory with the intention of achieving some goal. This suppressive form of active forgetting can help us update new information (new address), and adjust to our present surroundings (temporarily say "Hola" when in a Spanish-speaking country even if your first language is English). Although both blocking and suppression are examples of active forgetting and thus "retrieval inhibition," for the purpose of this paper, I will only label mechanisms that involve direct suppression as "inhibition." Blocking and other noninhibitory examples of forgetting will be termed "interference."

A lucid example of retrieval inhibition can be seen in a paradigm called Think/ No-Think (Anderson & Green, 2001). In this task, participants learn word pairs and are then cued with one word and asked to either suppress or recall the paired word. The suppress/ recall instructions affect participants' recall performance on subsequent tests so that they demonstrate poorer memory performance for the items that they were instructed to suppress in comparison with control items. Brain imaging studies have shown that while participants are attempting to suppress words, their brain activity resembles times when they are stopping prepotent motor responses (Mecklinger, Parra, & Waldhauser, 2009). This type of retrieval inhibition would be useful in helping us to override old and intrusive memories (e.g. introducing oneself with one's married over maiden surname).

Directed forgetting is another paradigm in which researchers have attributed behavioural findings to inhibitory mechanisms (Bjork, 1989). In the list-method directed forgetting paradigm, participants study two lists of words and are instructed to forget one of the lists. After a brief distracter phase, participants are asked to recall both lists. Results show impairment in the participant's ability to recall the list that they were told to forget and that participants remember the other list better than in the control conditions. The consensus regarding the underlying mechanisms of the poor recall performance for the to-be-forgotten list is not definitive (MacLeod et al., 2003).

Some authors attribute directed forgetting effects to inhibition (Bjork, 1989), others ascribe it to a strategy disruption hypothesis (Basden, Basden, & Morales, 2003), and some even attribute the effects to selective rehearsal (encoding failure, not retrieval[1]) (MacLeod et al., 2003). Regardless of underlying mechanisms, this paradigm is worth mentioning because it shares many parallels with the subject of our study: retrieval-induced forgetting. Researchers have dissociated the two memory-related phenomena as having two separate mechanisms (Basden et al., 2003), but many of the theories behind retrieval-induced forgetting are derived from the directed forgetting literature.

Whether memories that we wish to retrieve become temporarily inaccessible due to insufficiently specific retrieval cues, blocking by similar memories, or active inhibition, it is clear that the process of retrieving a specific memory is complex. Our brains must sort through an ocean of memories, many of them similar and related, in order to withdrawal a single, specific target memory; all while our memory continues to expand, update, and otherwise fluctuate. How do our brains accomplish this? MacLeod and Hulbert refer to this capability as "resolution power," or the ability to retrieve a particular memory. Authors argue that in addition to effectively labeling and organizing memories, our brains have evolved a mechanism that distinguishes contextually-appropriate information from contextually-inappropriate information to achieve the type resolution power we see in human memory (MacLeod & Hulbert, in press). One such mechanism, retrieval-induced forgetting, temporarily makes inappropriate or competing memories inaccessible, and in doing so, affords us a dynamic tool that may enhance our selective resolution power.

Retrieval-Induced Forgetting

Retrieval-induced forgetting refers to the phenomenon whereby the retrieval of some memories causes us to forget other, related memories. Similar to directed forgetting, participants study lists of words. After selectively retrieving some words from one list, participants demonstrate enhanced recall for the words they retrieved

[1] MacLeod *et al.* (2003) believe that selective rehearsal can account for both item and list methods of directed forgetting (MacLeod et al., 2003; Sheard & MacLeod, 2005). Sheard and MacLeod manipulated participants' amount of rehearsal by distracting them immediately after study or by announcing a financial incentive to recall as many words as possible and then giving them a delay (Sheard & MacLeod, 2005). They also manipulated factors such as serial position of the lists, and whether participants were given a delay after study or warned that all words would be recalled ("warning effect"). Together, their findings suggest that selective rehearsal makes a significant contribution to list method directed forgetting, and in their 2005 book chapter, they cite several other studies that agree with this hypothesis (MacLeod et al., 2003; Sheard & MacLeod, 2005).

and impaired recall for other words in the same list. Meanwhile, the recall for other, unrelated lists remains unaffected, and therefore serves as a baseline. Unlike directed forgetting paradigms, however, participants are not directed to "forget" any of the words; they seem to do this on their own. This non-directed form of forgetting seems to be generated by the selective retrieval of some words rather than by a coercive instruction to forget.

The basic retrieval-induced forgetting paradigm requires a participant to study lists of category-exemplar pairs. After studying the words in each category (e.g. FRUIT-ORANGE, APPLE, etc. and SPORTS-BASEBALL, SOCCER, etc.), participants undergo selective retrieval practice where they practice remembering some of the words from some of the categories. In many retrieval-induced forgetting experiments, participants are given the first letter as a unique cue, and then are asked to recall the entire word (e.g. FRUIT-O____). The words that the participants attempt to retrieve are called Rp+ items because they have undergone retrieval practice. The words that are in the same category as the practiced Rp+ items but which do not receive any retrieval practice are called Rp- items (e.g. APPLE). Finally, all of the words in the unpracticed categories are called Nrp items (e.g. BASEBALL) because none of the words in the Nrp category (e.g. SPORTS) have undergone retrieval practice (thus, the name Nrp: no retrieval practice).

Following the retrieval practice phase, participants typically engage in a distracter task such as a reaction time task or motor task for up to twenty minutes. After this brief distracter phase, participants are asked to recall all of the words from both categories in the final test phase. Rp+ words are recalled more than any other type of word. This facilitation effect is expected because participants have spent additional time retrieving these words. Researchers predicted that the facilitation of Rp+ items might also facilitate Rp- items even though both Rp- and Nrp words are treated the same throughout the experiment; the participants only see each word one time and have one chance to recall the words in the test phase. This prediction is derived from the notion that when participants attempt to remember some items (e.g. FRUIT-ORANGE), they may also bring to mind other words in the same category (e.g. all FRUITS). Therefore, if there is a difference in the recall of the two types of items, more Rp- words will be recalled. Interestingly, however, researchers have found the opposite; that Rp- words are recalled more poorly than the Nrp words (see Figure 1.1

for example of results). This reduction in recall performance for Rp- words in comparison with control words has been termed retrieval-induced forgetting (RIF).

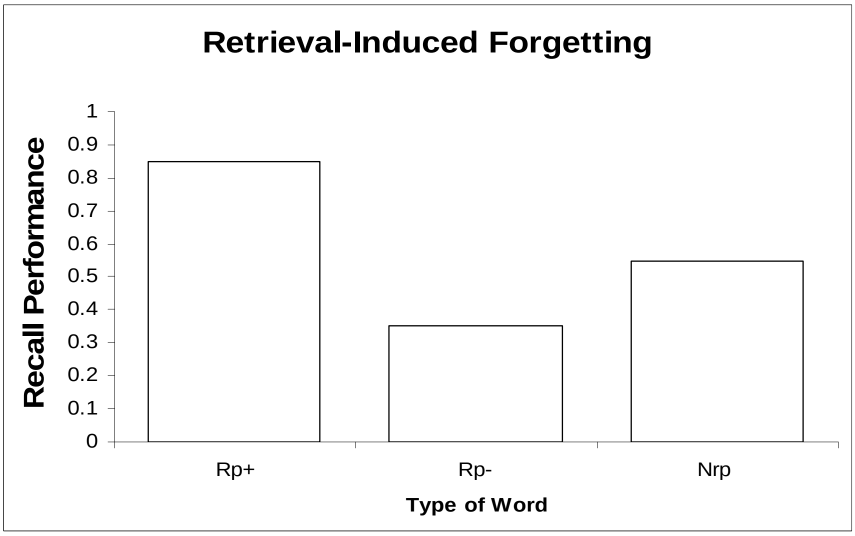

Figure 1.1 Example of behavioural results obtained from a retrieval-induced forgetting experiment.

Retrieval-induced forgetting has been demonstrated with a range of materials; shapes and colors, and details of crime scenes (Bauml, 2002; Ciranni & Shimamura, 1999; Shaw, Bjork, & Handal, 1995). The words within each category have been semantically related to each other (Anderson, Bjork, & Bjork, 1994) or have had no relation to each other at all (MacLeod, Saunders, & Chalmers, 2010). What seems to matter is that participants study sets of items in separate blocks and then selectively retrieve some items from one set of items. The subsequent forgetting of the unpracticed items is thought to be an adaptation that allows our brains to efficiently retrieve a specific memory without interference from related memories. The accumulation of studies regarding this phenomenon is changing the way we think about memory; that forgetting may be helpful, or even necessary, for optimal memory performance. As interesting as they may be, what do these laboratory findings tell us about human memory function in real world?

Fifteen years ago, researchers explored whether the “incomplete retrieval tasks” that eyewitnesses undergo in interviews and interrogations may impair their recall of information due to RIF (Shaw et al., 1995). The authors had participants study visual stimuli that depicted an event, questioned participants about some of the details of the event (retrieval practice), and then put participants through a final recall test (Shaw et al., 1995). They found that the participants remembered the information that they had been questioned about better than a control group that was not interrogated (facilitation). They also found that compared with the control group, the interrogated group demonstrated diminished recall for the details that were not part of the interrogation, or retrieval-induced forgetting. The authors concluded that the repeated questioning of eyewitnesses about details of an event may impair later recall of details that were not the object of the original interrogation.

MacLeod and Saunders (2008) extended these findings by introducing misinformation phrases into a standard RIF paradigm. The misinformation effect occurs when participants preferentially “remember” or report misinformation over a real memory when misinformation was given about the real memory (MacLeod and Saunders, 2005). To explore whether these misinformation effects contribute along with RIF effects to impair an eyewitness’s recall of an event, researchers introduced misinformation phrases into the interrogation phase (retrieval practice). The experiment demonstrated that only Rp- items were subject to misinformation effects. The findings of these two studies (MacLeod & Saunders, 2008; Shaw et al., 1995) have enormous implications for eyewitness testimony. For example, the initial questioning of eyewitnesses should be comprehensive to avoid impairing details that are overlooked or not discussed (MacLeod & Saunders, 2008). Secondly, authors suggested that authorities provide sufficient time to elapse after the initial interrogation to allow time for RIF effects to dissipate before an eyewitness gives a final statement. Thus researchers have used our current understanding of RIF to propose suggestions for improving the accuracy and completeness of testimony given by eyewitnesses.

Despite the accepted notion that RIF improves memory performance by allowing us to selectively retrieve a specific memory among a myriad of similar memories, eyewitness testimony presents an example where retrieval-induced forgetting may be detrimental to the task we are trying to achieve. How can we minimize the negative effects of RIF and optimize our memory retrieval? Besides integrating information or waiting for RIF effects to dissipate over time, are there other boundary conditions that eliminate RIF? As it turns out, there are. Mood appears to be one of these additional boundary conditions; inducing low-mood can eliminate retrieval induced forgetting entirely (Bauml & Kuhbandner, 2007). Consistent with this notion, a RIF study found an inverse correlation between an individual’s Beck Depression Inventory score and their degree of retrieval-induced forgetting (Groome & Sterkaj, 2010). Individuals with clinical depression did not demonstrate impaired recall for Rp- items even though they do show poorer recall performance overall (Groome & Sterkaj, 2010).

One explanation for these findings (Groome & Sterkaj, 2010) is based on the previously described notion that RIF is thought to assist in the selective retrieval of specific memories. It is intuitive then, that this phenomenon would be absent or defective in individuals whose illness is correlated with a tendency to generalize autobiographical memories. The deficiency in *selective* memory retrieval may explain why populations of individuals with other types of memory impairments such as the elderly (Hogge, Adam, & Collette, 2008) or people with Alzheimer's disease (Moulin et al., 2002) are still subject to retrieval-induced impairments while individuals with depression are not. These studies suggest that the cognitive processes responsible for retrieval-induced forgetting may function independently from other long-term memory processes. If this is the case, then *what are* the mechanisms behind retrieval-induced forgetting; what is our brain doing at the neural level?

Inhibition Theory

Michael Anderson *et al.* (1994) proposed that RIF may be caused by a competition-driven inhibitory mechanism. To ensure optimal retrieval of some items within a category, our brains may recruit executive control processes to actively inhibit other, competing items within the same category (Anderson, 2003).

Anderson supports the theory of inhibition with five major pieces of evidence:

1) Cue Independence: Recall of Rp- items is impaired independent of the cue, or category with which it was learned (e.g. learned APPLE as an exemplar of FRUIT). If participants are cued with a difference category in the test phase (e.g. RED-A___ instead of FRUIT-A___), RIF still occurs. Anderson argues that this cue-independent forgetting provides strong support for the idea that the competing memory itself (APPLE) is being inhibited (Anderson, 2003).
2) The RIF effect is "retrieval specific." While cue-independence provides evidence that inhibition is responsible for RIF, it does not rule out the possibility that other noninhibitory mechanisms, such as blocking, are also contributing to RIF. Blocking predicts that recalling the Rp+ items in the final

test phase may indirectly block the recall of unpracticed competitors because of limited resources (could be attention resources, resources to strengthen/maintain memory traces, etc.). Therefore, any type strengthening of Rp+ items would impair the recall of Rp- items because more resources are given to the Rp+ items leaving fewer resources available for the Rp- items. In a study that gave participants either traditional retrieval practice (FRUIT-O__) or an extra study exposure to the Rp+ words (FRUIT-ORANGE), only the participants who had retrieval practice demonstrated RIF (Anderson, Bjork, & Bjork, 2000). Several studies have replicated this finding (Johansson, Aslan, Bauml, Gabel, & Mecklinger, 2007; Wimber, Rutschmann, Greenlee, & Bauml, 2009), which demonstrates that the inhibition of the Rp- items is dependent on the selective retrieval of other items in the same category (e.g. Rp+ items). The fact that increased study exposure of the Rp+ items produces facilitation effects of these items but does not produce RIF, suggests that this type of blocking effect does not contribute to RIF.

3) Interference dependence: Selective retrieval is not enough in itself to produce RIF. Non-practiced items must pose as competition to recruit executive control processes, otherwise there would be no difference between the recall of Rp- and Nrp items. As it turns out, RIF can be manipulated by manipulating the strength of the Rp- items. Taxonomically stronger Rp- items generate more retrieval-induced forgetting (less recall of Rp- words) than do weak Rp- items. This finding supports a competition-based explanation for RIF because increased competition with the Rp+ items caused by stronger Rp- items produces larger RIF effects (Anderson et al., 1994).
4) Strength Independence: The magnitude of the RIF effect is independent from the strength of the practiced items. Increasing or decreasing the facilitation effects by manipulating the strength/ weakness of Rp+ items does not affect the amount of impaired recall of Rp- items. These findings provide further support against noninhibitory competition theories because RIF can occur at the same magnitude regardless of Rp+ strength, which according to blocking theories should influence the number of resources available for Rp- recall (Anderson et al., 1994).
5) Impossible retrieval: Successful retrieval of the Rp+ items during retrieval practice phase is not necessary to impair recall of Rp- items in final test phase.

This was demonstrated in a study where participants recalled novel items and impossible items, *instead* of Rp+ items, during retrieval practice (Storm & Nestojko, 2010). It appears that the retrieval attempts, or the memory search, in itself causes RIF effects. Noninhibitory theories such as blocking cannot account for these findings because they are based on the idea that Rp+ items and their facilitation are responsible for the impairment of Rp- items. In contrast, inhibitory theories are "strength independent," (see 4 above) and therefore do not require strengthening of Rp+ items to explain RIF effects.

It should be noted, however, that there are critics who challenge the effectiveness of independent cues in differentiating inhibition from blocking (Camp, Pecher, Schmidt, & Zeelenberg, 2009). These critics have demonstrated that independent cuing is not truly independent because participants draw from retrieval cues outside of the cues given to them at test, an effect called covert cuing. Thus, participants can still use the cues given in the study phase even when they are presented with "independent" cues at test. Furthermore, these results came from a study that only involved study and test phases. It is believed that retrieval practice phase would further enhance the accessibility of the cue/category, making it even more likely that it will be used as a covert cue at test (Camp et al., 2009). Despite this study, the authors of a brain imaging study (Bergström, de Fockert, & Richardson-Klavehn, 2009) argue that their findings provide strong evidence to support independent cues' ability to differentiate between inhibitory and interference mechanisms (see "Imaging Experiments" section). There is a need for more research that explores the extent to which participants engage in covert cuing and how this may influence forgetting in the RIF paradigm.

Lateral inhibition

Using the evidence above to conclude that RIF effects are caused by competition-driven inhibition, Anderson and Spellman (1995) further explored the mechanisms underlying RIF by differentiating two types of inhibition: lateral inhibition and pattern suppression. Lateral inhibition in RIF presumably acts in the same way as it does in sensory and motor systems. Inhibition occurs between members of a single "hierarchical level" (Anderson & Spellman, 1995). In the RIF paradigm, this means that inhibition occurs only between exemplars and not between category-exemplar connections. During retrieval practice, activation spreads from the Rp category to all items within the category. As participants attempt to retrieve Rp+ items, more activation is spread to those Rp+ items which then inhibit the Rp- items.

Lateral inhibition can account for cross category and second-order inhibition effects[2] due to the fact that all related items (even items in other categories) are connected and capable of mutually inhibiting each other. However, lateral inhibition cannot explain why second order inhibition occurs at a similar or sometimes greater magnitude to inhibition of Rp- items. According to the lateral inhibition theory, impairing Rp- items during retrieval practice phase should reduce the ability of Rp- items to inhibit related Nrp items. If this were the case, second-order inhibition would be reflected in smaller, echo-like impairments relative to the magnitude of Rp- recall. Since this is not the case, Anderson and Spellman found lateral inhibition to be inadequate even though they argued that it explains many aspects of RIF better than noninhibitory accounts.

Pattern Suppression

Pattern suppression is based on the notion that items share common, overlapping "features" with one another. These overlaps cause each item to accumulate activation both by the category and by activation of other associated items. During retrieval practice, the activation from category to Rp+ item spreads to all other related items; other Rp items *and* Nrp items. Selectively retrieving an Rp+ item would facilitate other items associated with this item (other Rp+ items and Nrp items related to Rp+ items) and impair competing items (Rp- items). This suppression during retrieval phase will make it more difficult to recall these Rp- items later. In addition, it will be more difficult to recall Nrp items that are related to Rp- items due to the overlap and common features that the Nrp items share with Rp- items. In contrast to lateral inhibition, this theory predicts that second-order inhibition will vary

[2] Cross-category inhibition refers to the inhibition of Nrp items that are semantically related to Rp items via a common category. For example, with Rp category RED, and Rp- item TOMATO, Nrp item CRACKER from Nrp category FOOD may also be inhibited with TOMATO because both items are foods. Second order inhibition is similar, but refers to the inhibition of Nrp items that share an *implicitly* semantic category that was not explicitly provided at study. If the Rp category-item pair is still RED-TOMATO and we have Nrp pair SOUPS- MUSHROOM, mushroom may be inhibited because tomatoes and mushrooms are both vegetables, a category that was never studied.

according to an Nrp item's relatedness to an Rp- item, not according to the degree of Rp- impairment.

Anderson and Spellman (1995) propose a numeric example to elucidate this concept. If 35% of an Rp- item's "features" overlap with the Rp+ item's features, retrieval practice would inhibit the 65% of distinctive Rp- features and leave the overlapping 35% active. If an Nrp item's features are 95% similar to the distinctive features of the Rp- item (the inhibited part), then 95% of that Nrp item's features will be inhibited. Since only 65% of the Rp- item's features are inhibited, in this example the Nrp item is actually more inhibited than the Rp- item. This model, therefore explains why second-order inhibition effects can vary to be less, similar, or greater than impairments in Rp- recall. In addition, Anderson and Spellman argue that this model best characterizes the mechanism that underlies RIF effects.

Strategy Disruption Hypothesis

Although a considerable portion of the RIF literature is consistent with Anderson's account of inhibition, other researchers have begun to theorize on different explanations for the neural mechanisms underlying the phenomenon. One of these theories, strategy disruption, was also used to explain the effects of list method directed forgetting (Basden et al., 2003). The notion here is that participants learn each list in the directed forgetting paradigm using a specific strategy or mental organization. When they are told to forget the first list, they abandon that strategy/order and reorganize their previous retrieval strategy to optimize their memory of the second list. Therefore, the differences in recall between control groups and those who were told to forget list 1 could be accounted for by a disruption in the order and organization of items in the participant's brain. If this theory extends to retrieval-induced forgetting, it would explain why RIF effects dissipate over time (MacLeod & Macrae, 2001) because items get reorganized as time moves away from the disruptive practice session (Dodd, Castel, & Roberts, 2006; Williams & Zacks, 2001).

In order to directly test the strategy disruption hypothesis with retrieval-induced forgetting, Dodd *et al*. (2006) modified a standard RIF paradigm to investigate whether RIF occurs when measures are taken to avoid disrupting participants' retrieval strategy during the retrieval practice phase. In their serial position practice conditions, participants underwent retrieval practice on the last five items that they studied, rather than on randomly selected Rp+ items. In their every-other-word practice condition, participants had retrieval practice on every other item from one of the categories, presuming that both of these conditions would not interfere with participants' retrieval strategies or mental organization. As predicted, neither of these conditions produced RIF effects while a control condition with randomly selected Rp+ items did. The authors replicated these findings in a second experiment by instructing participants to study items in the order with which they were presented, and then in a third experiment with a different RIF paradigm. With all three experiments producing the same results, the authors argue that this study provides sound evidence that disrupting the order in which participants organize the items in memory contributes to retrieval-induced forgetting effects.

The strategy disruption hypothesis, however, does not account for all RIF effects. Dodd *et al.* (2006) mentions that the hypothesis fails to account for cue-independence and argues that strategy disruption may be one component to a multi-process system that produces RIF effects. Despite this, it is still possible to explain cue-independence in terms of strategy disruption. According to this hypothesis, the memory strategy is disrupted and rearranged to optimize recall for the Rp+ items. When this happens, the Rp- items would be excluded from mental organization, giving Nrp items an advantage over Rp- items because they still maintain their original organization. Rp- items at test, regardless of the cue, would resemble items that have never been studied and never been practiced. If this were the case, then it may provide more evidence for the strategy disruption hypothesis.

Strategy disruption, however, fails to explain other RIF effects such as cross-category and second-order inhibition (Saunders & MacLeod, 2006). The strategy disruption hypothesis assumes that the Nrp categories are organized separately from the items in the Rp category (which is why Nrp items are not inhibited). Therefore, disrupting the organization of the Rp category through retrieval practice should not affect the organization and recall of the Nrp items. Thus as of now, the strategy disruption hypothesis remains incomplete. The hypothesis needs to undergo more investigation in order to explain all of the effects that characterize RIF before confirming it as the mechanism behind RIF.

Limited Spread of Activation and Resource Allocation

Another possible explanation for RIF effects is based upon a competitive model whereby connections exist not only amongst categories and items, but also between the items themselves (Oram & MacLeod, 2001). This idea is intuitive considering that Anderson's account of inhibition requires semantic relationships, and thus connections, between Rp+ and Rp- items. According to Oram and MacLeod's model, when a participant attempts to retrieve an Rp+ item from memory, they activate the connection between category and the Rp+ item, which also partially activates other items in the category that are connected to that Rp+ item (see Figure 1.4). None of this activation affects the connections or level of activation in the unrelated Nrp category, explaining why these items remain unaffected at test. This model can also account for cross-category and second-order inhibition effects because, like Rp- items, semantically related Nrp items are partially activated during retrieval practice and therefore weakened relative to items not linked to Rp items/category (Saunders & MacLeod, 2006).

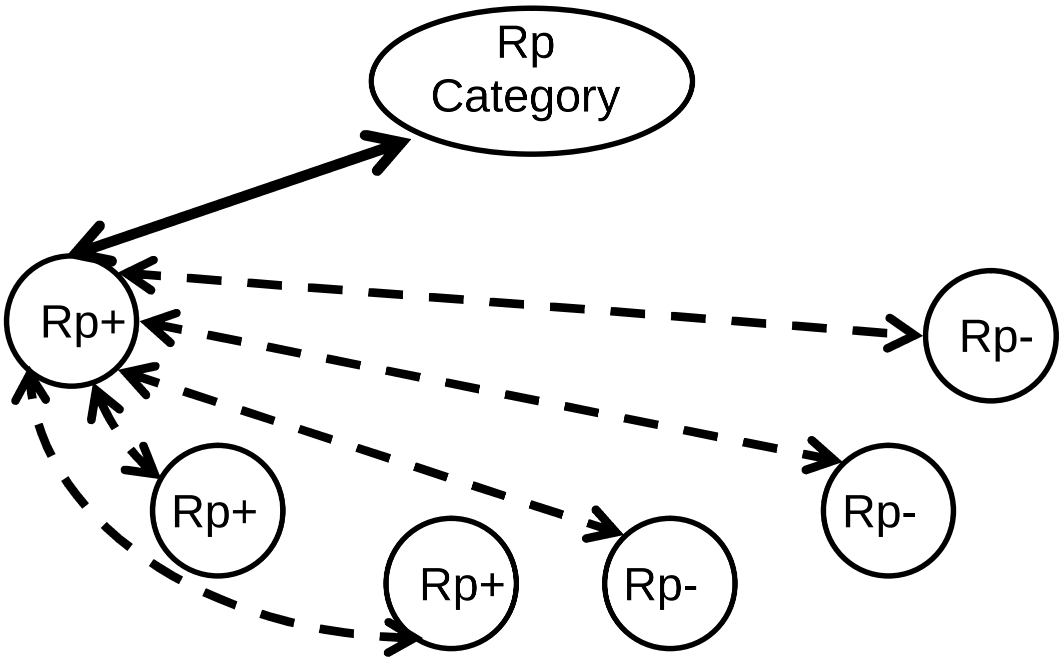

Figure 1.4 Limiting the Spread of Activation: retrieval practice phase spreads activation between category and the item being retrieved (solid line). When this item is retrieved, part of that activation is spread to all of the items connected to that item (dashed lines).

The model, described as "limited spread of activation," not only accounts for RIF effects previously seen in the literature, but also successfully predicts other RIF effects. In Oram and MacLeod (2001), three scenarios are explored using a computational model that predicts when RIF will and will not occur. The model predicts that RIF would not occur when all items were studied together rather than in separate blocks/categories. When studied randomly, the retrieval practice phase partially activates all of the items in all of the categories because there are connections between all of the items (they are not temporally separated into categories). The result is reduced recall of Rp- *and* Nrp items due to increased competition and partial activation of those items. While the Rp+ recall performance is still better than the other item types, the facilitation effect is reduced due to the limited amount of activation spread across all item types. A behavioural experiment confirmed this prediction.

The second prediction of the model involved semantic links between items in the Rp category and items in the Nrp category. Words in the Nrp category that are semantically-related to the Rp category will be partially activated, and like the Rp- items inhibited (similar to cross-category and second-order inhibition). Therefore, you see an increase in Rp+ recall performance and a decrease in both Nrp and Rp- recall, eliminating the RIF effect. In the final prediction, the model predicts that RIF would not occur when the two categories are semantically related, because again both Nrp and Rp- recall will be reduced. This prediction was also confirmed in a behavioural experiment.

The findings of these experiments coincide with those of related studies. Similar to Oram and MacLeod's second experiment in their 2001 study, Anderson and McCulloch (1999) found that "integration" also eliminated RIF effects. The authors instructed participants to make relationships between the items during the study phase. Participants who "integrated" the most exhibited more markedly reduced RIF. Interestingly, the Rp+ items were also affected, showing 18% decrease in recall from a control condition. While Anderson and McCulloch were unable to explain this finding with their inhibitory theory, the limited spread of activation model can. Due to the relationships between items, when Rp+ items were practiced, all items that had been "integrated" with those items were partially activated (even other Rp+ items). Similar to the findings in Oram and MacLeod's first experiment, the spread of activation across all item types may have lead to a decrease in overall recall performance.

There is another effect in the memory literature that seems consistent with the limited spread of activation theory: the fan effect. The fan effect is the increase in time it takes for a participant to retrieve a particular fact about a concept after you associate more facts with that concept, or increase the size of the fan. John Anderson and Lynn Reder (1999) explored the mechanisms behind the effect and found the effect most attributable to "associative interference," which shares many parallels with the limited spread of activation theory. With the fan effect, the strength of an association between a concept (category) and a fact (item) is adjusted according to prior experiences to reflect the statistical regularity with which the concept predicts that fact. As the fan increases, a concept becomes a poorer predictor, and latencies increase (recall performance diminishes). Similar to the limited spread of activation theory above, latencies are based on the level of activation of an item and not the level of suppression. The same mechanisms can be seen to cause facilitation and inhibitory effects.

While these parallels provide additional support for the limited spread of activation theory, it is important to note the significant differences between J. Anderson and Reder's experiment and the traditional RIF paradigm (J. R. Anderson & Reder, 1999). Anderson and Reder used recognition instead of recall in the final test, and measured reaction time instead of recall performance. Thus, while a theory of limited spread of activation may explain the fan effect, we cannot conclude that the same mechanism is behind RIF effects. It would be best to apply a fan-type manipulation to a RIF paradigm, and see if such a study provides insights into the mechanisms behind RIF effects.

Using Anderson's "associative inference" theory for the fan effect, M. Anderson's integration paper, and Oram and MacLeod's competitive network model, the current study was designed to amalgamate some of these findings and specifically test whether a limited spread of activation is one of the mechanisms underlying RIF. In this paper, we refer to the culmination of these theories and our own hypothesis as "resource allocation" because these theories fit an interpretation that RIF effects can be manipulated by differentially allocating the finite amount of attentional resources available to each category.

According to the fan effect, the more facts associated with a concept, the weaker the associations from concepts to facts. Following this logic, the more Rp+ items, the weaker the connections from Rp+ items to category, because activation is being spread amongst all of the Rp+ items. With less activation being spread across each Rp+ item, and with fewer number of Rp- items, you might expect there to be more activation available for the few Rp- items. Thus, activation is spread more evenly across items, and we would expect a reduction in facilitation effects, and an increase Rp- recall enough to eliminate RIF; similar to Oram and MacLeod's first experiment and the results of Anderson's integration paper.

In contrast, Anderson's inhibitory theory would predict that that RIF would still occur, but that some of the Rp+ items would be inhibited as well. According to M. Anderson's account, inhibition occurs in the retrieval practice phase. By the time the participant tries to retrieve some of the last Rp+ items, inhibition will have already begun, so some of the last Rp+ items to be recalled may be inhibited as well. Since Oram and MacLeod's model predicts a different behavioural outcome than Anderson's, we based our behavioural experiment on this manipulation of Rp+ items.

Our behavioural study consisted of three different experiments: one control experiment and two experiments to compare and contrast results with different number of Rp+ items. The first experiment was our control. Experiment 1 resembled the standard retrieval practice paradigm (5 Rp+ items) and was therefore called *Retrieval Practice Paradigm* (RPP). In our second experiment called *Increase Rp+ Items*, we tested our resource allocation hypothesis by increasing the number of Rp+ items to 10 Rp+ items. For the third experiment, *Increase Rp- Items*, we used the same large categories as the second experiment (two categories of 15), but set the number of Rp+ items at 5, giving us 10 Rp- items. This way, if there was a difference in retrieval-induced forgetting between Experiments 1 and 2, we could distinguish whether the difference was attributable to the varying number of Rp+ items (5 versus 10 Rp+ items), or the varying size of category (10 versus 15 items in each category).

Our hypothesis was that manipulating of the number of Rp+ items would influence RIF effects. More specifically, we expected that both the RPP and Increase Rp- Items experiments (Experiments 1 and 3) would produce RIF effects, but that the Increase Rp+ Items experiment (Experiment 2) would not. We hypothesized that by increasing the number of Rp+ items, the limited activation available for the Rp category would be spread out more evenly among Rp items, thereby reducing facilitation effects and enhancing Rp- recall performance to resemble Nrp recall.

Imaging Experiments

In addition the behavioural evidence, a large portion of the memory retrieval literature uses brain imaging to explore the neural processes behind intentional forgetting. One such study, recorded event-related potentials (ERPs) while participants underwent a modified version of the Think/ No-Think paradigm to discern the neural differences between two different types of retrieval stopping (Bergström et al., 2009). In the traditional Think/ No-Think paradigm, participants are cued to either think or to not-think of the word presented to them depending on the color of font (green/red). In the modified version, participants are given the specific strategy of substituting another word into mind when the no-think words are presented. The two methods produce the same behavioural results (participants demonstrate poorer recall for the “no-think” words), but researchers hypothesized that the traditional paradigm recruits inhibitory processes whereas the substitution method uses blocking/ interference mechanisms. Behaviourally, the only evidence to support this hypothesis was with the use of independent cues which selectively elicit forgetting in the traditional paradigm, but not with substitution. Cue-independence in the traditional paradigm does provide support for the inhibition hypothesis. However, as described previously (Camp et al., 2009), there is a degree of uncertainty regarding independence cues, and such behavioural findings therefore are not definitive.

Where behavioural studies had failed, the Bergström *et al*. study (2009) succeeded in dissociating the traditional method from substitution due to the addition of imaging evidence. Both strategies produced forgetting in the behavioural experiments, but only direct memory suppression elicited reduced centro-parietal positivities. In addition, direct memory suppression produced forgetting that was predicted by an early negative ERP effect at parietal electrodes, similar to that seen in motor inhibition. This study provides two crucial pieces of information about intentional forgetting: 1) that there are electrophysiological differences between inhibition and blocking (inhibitory and non-inhibitory forgetting), and 2) that cue-independence is a behavioural measure that can accurately dissociate the two mechanisms in the Think/ No-Think paradigm.

In the literature of retrieval-induced forgetting, imaging studies have varied in the types of RIF paradigms employed, and the phases in which the authors record brain activity. One fMRI study recorded during retrieval practice phase when participants engaged in either a retrieval practice condition or a relearning condition. In the retrieval practice condition, authors found activity in the anterior cingulate and dorsolateral-prefrontal cortices could predict retrieval-induced forgetting (Wimber et al., 2009). This activity was absent in the relearning condition, and so were RIF impairments. Due to the behaviourally predictive nature of the brain activity, the authors considered these findings to be consistent with Anderson's inhibitory theory which states that the mechanisms responsible for RIF occur during retrieval practice phase (Anderson & Spellman, 1995).

Following this line of thought, Johansson *et al.* (2007) recorded ERPs during retrieval practice phase. The authors compared ERPs from a standard retrieval practice to a relearning (extra study) condition, and found more positive-going ERPs over frontal regions in the retrieval condition. Their conclusion was that these late positive-going ERPs (1000-2000 ms) represented some of the neural correlates of inhibition because they could predict RIF effects. However the condition itself, relearning or retrieval practice, predicted RIF. To me, it therefore seems likely that Johansson *et al.* found the differences between selective retrieval and additional study rather than the neural correlates of RIF.

There is, however, another EEG study in RIF literature that provides better insights into the neural mechanisms responsible for RIF effects. This study recorded ERPs during the test phase of a RPP to examine the after-"effects" of inhibition, or the electrophysiological differences between item types at test phase. Recognition of Rp+ items elicited an increased late parietal positivity (LPP) in comparison to ERPs elicited by Nrp items (Spitzer, Hanslmayr, Opitz, Mecklinger, & Bauml, 2009). While the LPP increased with the facilitation of Rp+ items, it did not change relative to controls for recognition of Rp- items. If facilitation and reduced Rp- performance are mediated by the same mechanism as in our resource allocation hypothesis, you might expect the LPP to be reduced for Rp- items. Instead, Rp- recognition was determined by a frontal P2 component, and the authors concluded that the beneficial and detrimental effects of RIF are mediated by different processes (Spitzer et al., 2009).

Although the authors find their results in consistence with the theory of inhibition, it is not entirely clear whether the mechanism the authors were measuring was due to inhibition, attention/control, or recognition or the retrieval-cue. The fact that they found reduced amplitudes of the P2 ERP component that could predict the amount of retrieval-induced forgetting provides evidence that they were recording neural correlates of forgetting Rp- items. However, the increased LPP for recognition of Rp+ items may be due to the fact that participants have already seen these cues during retrieval practice. For the participants, it was the first time they were represented with Rp- and Nrp retrieval cues, and the first time they attempted retrieval of these items. This novelty in itself could have contrasted with Rp+ cues with which participants may recognize, sense familiarity for the answer, respond faster to, etc. To rule out these possibilities, it would have been useful to have recorded during the retrieval practice phase when the participants viewed the Rp+ cues for the first time. Comparing those ERPs to the ERPs elicited at test would provide another baseline/ control and provide more evidence to support the authors' conclusions.

Each imaging study described above provides one piece to a larger puzzle depicting the neural mechanisms that underlie RIF. Johansson *et al.* (2007) followed the assumption of Anderson's inhibitory theory that the neural mechanisms behind RIF occur during retrieval practice phase. If the mechanism responsible for decreased recall performance of Rp- items occurred after the practice phase, during the distracter phase, or the test phase, Johansson *et al.* would not know what the neural correlates of RIF were. Likewise, Spitzer *et al.* (2009) only recorded during test phase and therefore did not know if their findings represent neural mechanisms or RIF or the differences between viewing information for the first time since study versus viewing already relearned material. It is necessary therefore, for a study that records at both of these phases, and at study as well, to observe neural activity throughout the retrieval practice paradigm. When do neural processes for Rp- items begin to differ from Nrp items? What kind of processes are these and where do they occur? Are these processes different than those that facilitate Rp+ recall? The imaging component of our study was aimed at answering some of these questions.

The Present Study

Anderson's retrieval practice paradigm (Anderson et al., 1994) is well-known in the RIF literature and has been confirmed by other authors to produce reliable results. However, we chose to use a modified version of the retrieval practice paradigm by MacLeod, Saunders, and Chalmers (2010) because it provided the same replicability (MacLeod, 2002; MacLeod & Macrae, 2001; MacLeod & Saunders, 2005; Macrae & MacLeod, 1999; Shaw et al., 1995), and also was easier to adapt to the current study. In this version of the retrieval practice paradigm, there are two categories, each with 10 items: 5 Rp+, 5 Rp-, and 10 Nrp. To test our hypothesis, we needed to increase the number of Rp+ items. Williams and Zacks used 12 items per category (6 Rp+ , 6 Rp-) in their version of RPP, and still produced RIF (Williams & Zacks, 2001). Knowing that 12 items/category can sustain RIF effects, we were assured to expand our category size to have 15 items each to better accommodate methodological requirements of EEG experiment. With 15 items in each category, we were able to break each category into 3 subsets of 5 words, from which we rearranged to create our different experiments (see Figure 2.1 in Methods section for breakdown of each experiment).

Exp 1) Retrieval Practice Paradigm: This experiment was designed to replicate the standard retrieval practice paradigm (MacLeod, Saunders, & Chalmers, 2010) with two categories of 10 items each (5 Rp+, 5 Rp-, 10 Nrp). This experiment controlled for the variation in Rp- items and amount of retrieval practice in Experiments 2 and 3. Here, we used the same materials (two categories with 15 words) as in the other two experiments, but rotated the subsets so that there were only four subsets used at a time.

Exp 2) Increase Rp+ items: In the second experiment, we tested our resource allocation hypothesis by increasing the number of Rp+ items to 10, giving us 10 Rp+ items, 5 Rp- items, and 15 Nrp items. Our materials consisted of the same two categories and 6 subsets that were employed in Experiment 1.

Exp 3) Increase Rp- Items: This experiment was designed to be a direct comparison with Experiment 2. We used 15 items in each category, but this time employed the standard number of 5 Rp+ items instead of 10. Due to the large category size, this meant that there were 10 Rp- items in this experiment. As mentioned above, Experiment 1 controls for this varying amount of Rp- items. In addition, methodological constraints of our ERP procedures required us to present Rp+ cues three times in Experiment 2, and six times in experiment 3 (both total 30 presentations of cues). Previous studies have shown that repeating retrieval practice multiple times (authors repeated retrieval practice 1,3, and 6 times in the study) does not affect RIF effects (Macrae & MacLeod, 1999). Even still, Experiment 1 controls for this variation as well by only presenting participants Rp+ retrieval cues three times.

The Present Imaging Study

Our behavioural study provided the framework from which to test our hypothesis. However, the behavioural results in themselves may not have been sufficient to make conclusive statements regarding the underlying mechanism of RIF. Thus, equally important to our behavioural experiment was our plan to examine the electrophysiological correlates of retrieval-induced forgetting.

We designed this part of the study in conjunction with our behavioural study in the hopes of gaining insights to the neural processes responsible for behavioural differences between conditions. Originally we planned to record EEG during the Increase Rp+ Items and Increase Rp- Items experiments. However, due to the absence of retrieval-induced forgetting, we restricted recording to the Increase Rp+ Items experiment only, which would still allow us to observe neural processes as they change throughout the RIF paradigm. Aimed to monitor differences in ERPs throughout the RIF paradigm, we recorded in all three phases: study, retrieval practice, and test phase. Details regarding the onsets of recordings and specific regions of interest can be found in the Methods section under “Experiment 2, Procedures: EEG”.

METHODS

Participants:

Ninety-two psychology students from the University of St. Andrews aged 18 through 30 volunteered to participate in this study. Participants were told that they would participate in a computer task that would test memory performance and gave informed consent before the experiment began. Participants were compensated £3 for the behavioural experiments and £8 for Experiment 2 involving electroencephalography (EEG). A recall performance criterion was employed whereby participants' data were included in the study if they recalled at least 50 percent of Rp+ items either in the retrieval practice phase or in the test phase. Overall, 19 participants (6=RPP condition, 5=RA condition, 8=control condition) with a total average of 31 percent for Rp+ recall performance were disqualified.

This study employed a mixed design where the between-subjects variable placed participants in one of three experiments, and the within-subjects variable allowed us to compare participants' performance across three tests at test phase. Thirty-two students participated in the Experiment 1 (mean age= 23, 23 females), 24 in Experiment 2 (mean age= 21. 15 females), and 36 in Experiment 3 (mean age= 21, 24 females)

Experiment 1: Retrieval Practice Paradigm

Materials:

Materials were based on those used in MacLeod *et al.* (2010) but were adapted to fit the current paradigm (see Appendix A for details). Our materials consisted of descriptions of two fictitious planets: RUPPLE and MINOSCO. Each planet represented a category and contained 15 descriptive sentences about the planet. At the end of each sentence was the word that was to be remembered. For example, THE SKY IN RUPPLE IS TURQUOISE.

The number of Rp+, Rp-, and Nrp items varied in each experiment (Figure 2.1 summarizes the manipulation of materials). In this experiment, there were 10 items in each category: 5 Rp+, 5 Rp-, 10 Nrp. The categories were balanced so that half of the participants had planet Rupple for the Rp items and the other half had planet Minosco for the Rp items. The order in which the participants studied the categories was also

balanced so that half of the people who had Rupple for their Rp items studied Rupple first and the other half of the people with the same materials studied Minosco first.
All six of the subsets were balanced for word frequency (Francis & Kucera, 1982) and word length. Efforts were made to avoid words that were semantically related to each other or words that carried emotional valence. The initial two letters of each word were unique from the other words. In addition, data from a pilot experiment was used to calculate a "memorability" score (see Appendix B). This score was based on how many participants recalled a given word as an Nrp item in the first test of the test phase. These memorability scores, combined with word length and word frequency, determined the grouping of the words for each category (see Figure III, Appendix B). The full list of materials can be found in the appendices (Figure II, Appendix A). In this first experiment, only four of the six subsets were used at one time. However, subsets were rotated so that all subsets served as an Rp+ subset equally.

	Study			Retrieval Practice	Distracter Task	
	Category 1		Category 2			
	Rp+	Rp-	Nrp			
Experiment 1: Retrieval Practice Paradigm	1 2 3 4 5	6 7 8 9 10	11 16 12 17 13 18 14 19 15 20	1 2 3 4 5 } X 3		All <u>20</u> items are cued at random
Experiment 2: Increase Rp+	1 2 3 4 5 6 7 8 9 10	11 12 13 14 15	16 23 17 24 18 25 19 26 20 27 21 28 22 29 30	1 2 3 4 5 6 7 8 9 10 } X 3		All <u>30</u> items are cued at random
Experiment 3: Increase Rp-	1 2 3 4 5	6 7 8 9 10 11 12 13 14 15	16 23 17 24 18 25 19 26 20 27 21 28 22 29 30	1 2 3 4 5 } X 6		All <u>30</u> items are cued at random

Figure 2.1 Behavioural design for the three experiments of this study. The experiments differ in the number of Rp+ items, number of overall items in each category, and in amount of retrieval practice.

Procedures:

This experiment consisted of four phases: study, retrieval-practice, distracter, and final test. The details regarding the duration in which we presented the materials, as well as intervals between materials, were based on the methods described in Johansson et al. (2007). In the current study, however, the category in the study phase was presented for 4 seconds (s) instead of 3s to allow time for participants to read a whole sentence instead of a the one-word category employed by Johansson *et a*l.

In the study phase, participants were instructed to remember the study items presented to them on the screen. The participants were shown the category, RUPPLE, at the beginning of the study block one time for 3 s. Next there was a 2-s blank screen and 1s fixation cross, before the screen presented a sentence that described the category (e.g. THE SKY IN RUPPLE IS) for 4 s. The presentation of the sentence was followed by the study item in all capital letters, TURQUOISE, for 3 s. This sequence repeated, starting with the 1-s fixation cross, within one category until all 10 items

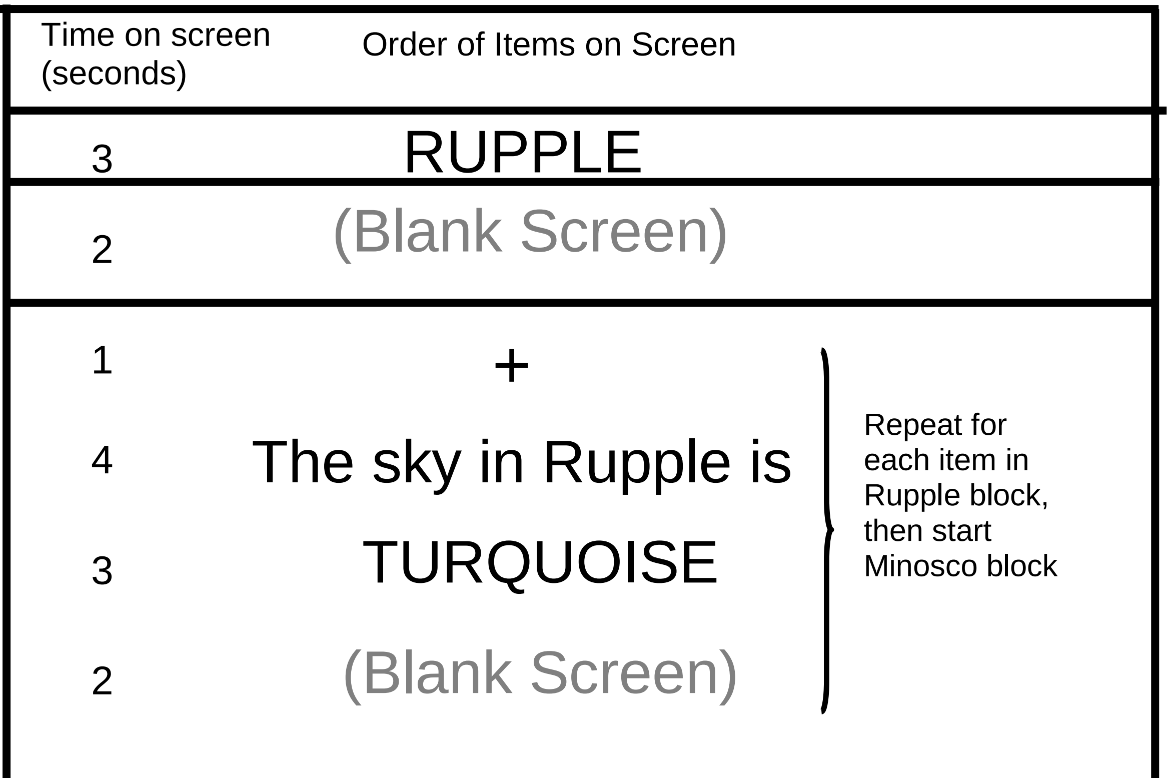

Figure 2.2 Sequence in which participants viewed information during the study phase. Each item was presented in black font in the centre against a white background.

had been shown once in random order (see Figure 2.2 for illustration of these procedures). The sequence then continued onto the next category and repeated until all of those 10 items were shown in random order. These procedures for the study phase were the same across all three experiments.

In the second phase, the retrieval-practice phase, participants were instructed to retrieve some of the study items. The items were presented in a similar way as before in the study phase except that participants were not shown the sentences. Presentation began with a 1-s fixation cross followed by the category, Minosco or Rupple, for 3 s. Next, participants were presented with the word stems (e.g. TU______) instead of the whole study word for 3 s. After the word stems, a question mark was presented for 2 s during which participants were instructed to respond orally. After the question mark, the sequence repeated started with the fixation cross. Unlike the study phase that only showed the category once at the beginning, in this phase Minosco or Rupple was shown in each sequence. In this experiment, the sequence was repeated until all Rp+ stems have been shown 3 times, for a total presentation of 15 word stems. The experimenter wrote down the participants' responses only if the participants responded during the 2-s presentation of the question mark. Any correct answers that were said after this time were scored as incorrect.

The third phase consisted of a filler task that was unrelated to the first two phases. Participants were given a two-choice decision task. They were shown letter stimuli (e.g. X or D) and asked to press one of two buttons to denote the letter that they saw. The participants were instructed to work as quickly as possible, and not to worry about accuracy. This ensured that they were thoroughly distracted and unable to think about the study materials. This distracter task lasted approximately 3 minutes.

The final phase was the test phase where participants attempted to retrieve all items shown in the study phase. The timing of this phase was identical to the retrieval practice phase. Each test started with a 1-s fixation process and then the presentation of a category for 3 s. Next, participants were cued with a 3-s presentation of the word stem. The presentation of the word stem was followed by a 2-s presentation of a question mark where participants are told to respond orally. The sequence repeated until cues for all 20 of the original study items had been shown once. All of the item cues were presented a random order. Again, the experimenter wrote down the participants' responses only if the participants responded during the 2-s presentation of the question mark.

Experiment 2: Increase Rp+ Items

Materials:

The materials for Experiment 2 involved the same study items and planet names as Experiment 1, but all six subsets were used at the same time instead of rotating four subsets at a time. In this experiment, each category had 15 items instead of 10. There were 10 Rp+ items, 5 Rp- items, and 15 Nrp items.

Procedures:

Experiment 2 followed the same procedures as in Experiment 1 for the study and test phases except that a total of 30 items were presented/ tested instead of 20. During the retrieval practice phase, participants practiced retrieving each Rp+ word three times, for a total presentation of 30 words. The distracter phase used the same paradigm but was lengthened to last for 10 minutes instead of 3. Additionally, we recorded brain activity using EEG on all of the participants who took part in Experiment 2 (see EEG part of methods for details).

Experiment 3: Increase Rp- Items

Materials:

Experiment 3 employed the same materials as Experiment 2. However, in this experiment there were 5 Rp+ items, 10 Rp- items, and 15 Nrp items.

Procedures:

Experiment 3 followed the same procedures as 2 for the study and test phases with a total of 30 items being studied/tested. During the retrieval practice phase, participants practiced retrieving each Rp+ word six times, for a total presentation of 30 words. As in Experiment 2, this experiment used the lengthened version of the distracter phase (10 minutes).

EEG Materials:

The materials for EEG recordings consisted of a BIOSEMI Active-Two amplifier system with 72 Ag/AgCl electrodes. Four external electrodes were placed to the sides of the eyes and below the eyes, to control for vertical or lateral eye movements. Two additional electrodes were used as reference and ground electrodes (Common Mode Sense active electrode and Driven Right Leg passive electrode), the latter to reduce the effect of external interference. Recordings were conducted in a Faraday cage, designed to shield external electrical interference as much as possible. EEG and electrooculogram (from external electrodes) recordings were sampled at 256 Hz. Offline all EEG channels were recalculated to average reference. Horizontal electroocular waveforms were calculated as follows: hEOG(t)=F9(t) minus F10(t). Trials containing eye blinks were corrected using a dipole approach (BESA Version 5.1.6). This description of materials has been acquired from previous studies for which the materials were acquired (Dudschig & Jentzsch, 2008).

Word stimuli were presented on an Envy 17-in. monitor controlled by an IBM-compatible personal computer. All stimuli were presented in black font in the centre of the screen (white background).

EEG Procedures:

EEG set-up and recordings were all conducted by the same experimenter. Set-up began by applying the external and ground electrodes to the face and mastoids. After measuring the participant's head, the electrode caps and electrodes were applied. The reference electrodes were applied last to a posterior medial part of the cap. Participants were then moved into the electrically shielded room where the lights were turned off to allow for optimal viewing of the computer monitor and stimuli. The experimenter connected the electrodes to the amplifier and then checked the quality of the signal on the computer. Once the experimenter confirmed that all electrodes were recording properly, the participants were instructed to begin the behavioural experiment. Recordings were taken during study phase, retrieval practice phase, and the test phase. During these phases, event related potentials (ERPs) were time-locked to the onset of the study word (200 ms before and for 1200ms).

During retrieval practice and test phase, participants were asked to move as little as possible to avoid producing movement artefacts with the EEG recording. Likewise, they were told only to speak their responses while the question mark appeared on the screen. By the test phase, most participants followed these directions accurately, limiting most motor movements to a 2-s window.

RESULTS

Behavioural

Experiment 1: Retrieval Practice Paradigm

A two-way ANOVA was run with within-subject factors test (1st, 2nd, or 3rd test during test phase) and item type (Rp+, Rp-, or Nrp). There was a significant main effect for test ($F(1.62, 50.22) = 27.72$, $p < .0001$, Mauchly's assumption of sphericity was violated $\chi^2(2) = 10.12$, $p < .01$, therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (epsilon =.81)) and item types ($F(2, 62) = 22.47$, $p < .0001$, assumption of sphericity met $\chi^2(2) = 4.32$, $p > .05$). Contrasts revealed that overall recall performance increased significantly with each test. Participants remembered significantly more items in Test 2 when compared with Test 1 ($F(1, 31) = 22.77$, $p < .001$), and also significantly more items in Test 3 when compared with Test 2 ($F (1, 31) = 15.04$, $p < .001$). For item type, pairwise comparisons revealed a significant facilitation effect (difference between Rp+ and Nrp, $p < .0001$), but contrasts showed no retrieval induced forgetting (differences between Nrp and Rp- recall ($F(1, 31) = 1.64$, $p =.21$). See Figure 3.1 for overall results of Experiment 1.

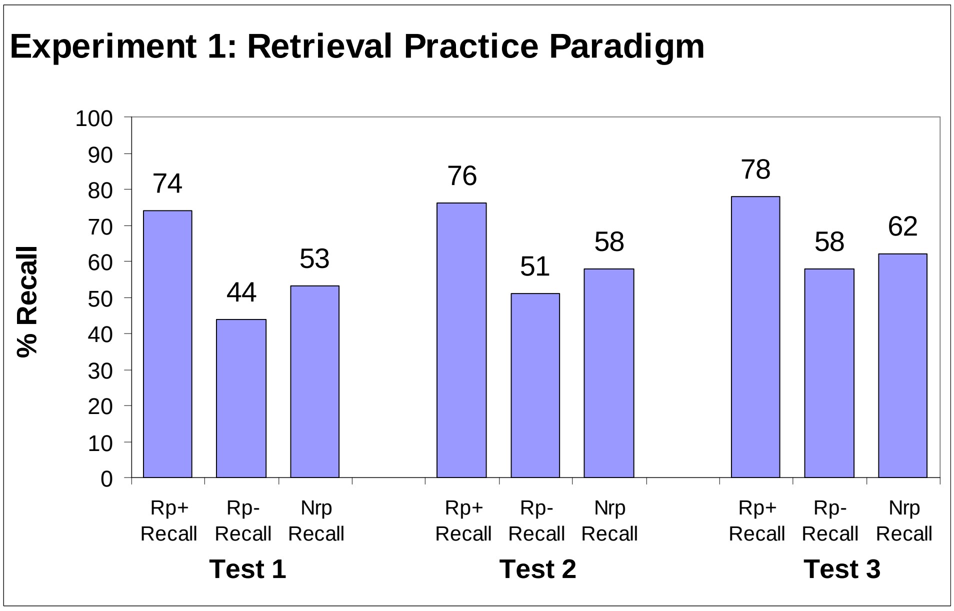

Figure 3.1 Behavioural results from Experiment 1. Each test produced facilitation effects, but no retrieval-induced forgetting. Recall performance improves with each test.

Our results demonstrate that recall improved with more retrieval attempts regardless of item type (Rp+, Rp-, or Nrp) so that recall performance was the best in the third test for all item types. These tests all occurred in the same 15 minute block. Since RIF effects have been shown to persist for at least 20 minutes, if we had observed RIF, we could have expected recall for Rp- items would not have shown any improvements.   To the contrary, the mean recall performance for Rp- items in this experiment increased by 14% from test 1 to test 3.

Experiment 2: Increase Rp+ Items

A two-way ANOVA was run with within-subject factors test and item type. There was a significant main effect for test ($F(2, 46) = 21.24$, $p < .0001$, assumption of sphericity met $\chi^2(2) = 2.61$, $p > .05$) and item types ($F(2, 46) = 7.75$, $p < .01$, assumption of sphericity met $\chi^2(2) = 5.94$, $p > .05$). Contrasts revealed that overall recall performance increased significantly with each test. Participants remembered significantly more items in Test 2 when compared with Test 1 ($F(1, 23) = 20.60$, $p < .001$), and also significantly more items in Test 3 when compared with Test 2 ($F(1, 23) = 7.05$, $p < .05$). For item type, pairwise comparisons revealed a significant facilitation effect (difference between Rp+ and Nrp $p < .0001$), but contrasts showed no retrieval induced forgetting (differences between Nrp and Rp- recall $F(1, 23) = 1.32$, $p=.26$). See Figure 3.2 for overall results of Experiment 2.

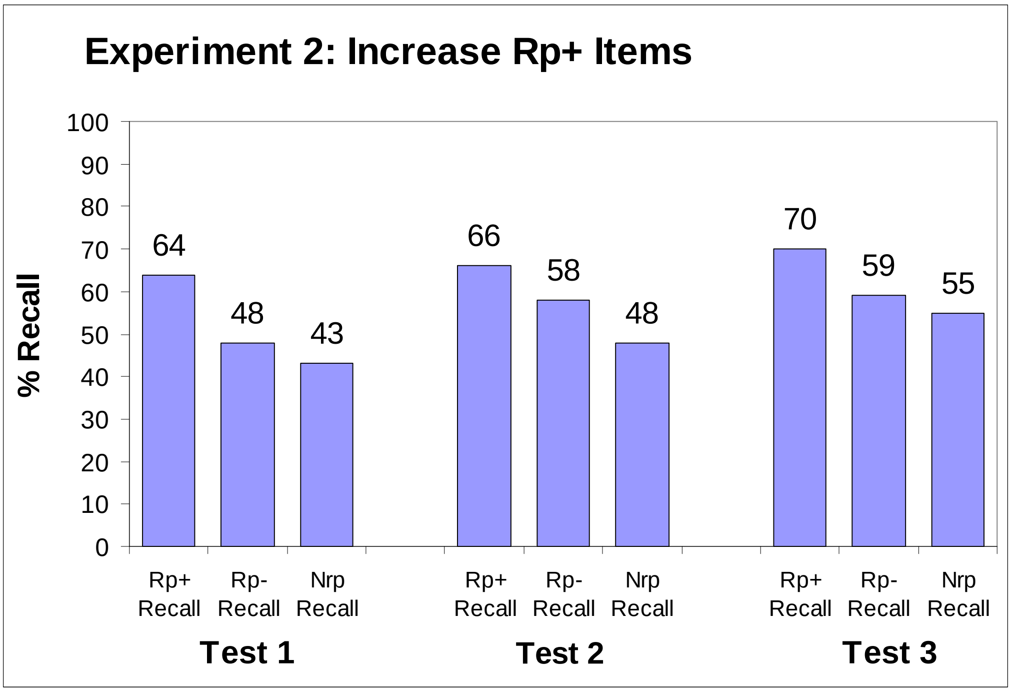

Figure 3.2 Behavioural results from Experiment 2. Each test produced facilitation effects, but no retrieval-induced forgetting. Recall performance improved with each test.

Experiment 3: Increase Rp- Items

A two-way ANOVA was run with within-subject factors test and item type. There was a significant main effect for test ($F(2, 70) = 34.41$, $p < .0001$, assumption of sphericity met $\chi^2(2) = 2.54$, $p > .05$) and item types ($F(2, 70) = 34.64$, $p < .01$, assumption of sphericity met $\chi^2(2) = .71$, $p > .05$). Contrasts revealed that overall recall performance increased significantly with each test. Participants remembered significantly more items in Test 2 when compared with Test 1 ($F(1, 35) = 9.79$, $p < .01$), and also significantly more items in Test 3 when compared with test 2 ($F(1, 35) = 29.41$, $p < .001$). For item type, pairwise comparisons revealed a significant facilitation effect (difference between Rp+ and Nrp $p < .0001$), but contrasts showed no retrieval induced forgetting (differences between Nrp and Rp- recall $F(1, 35) =.32$, $p =.58$). See Figure 3.3 for overall results of Experiment 3.

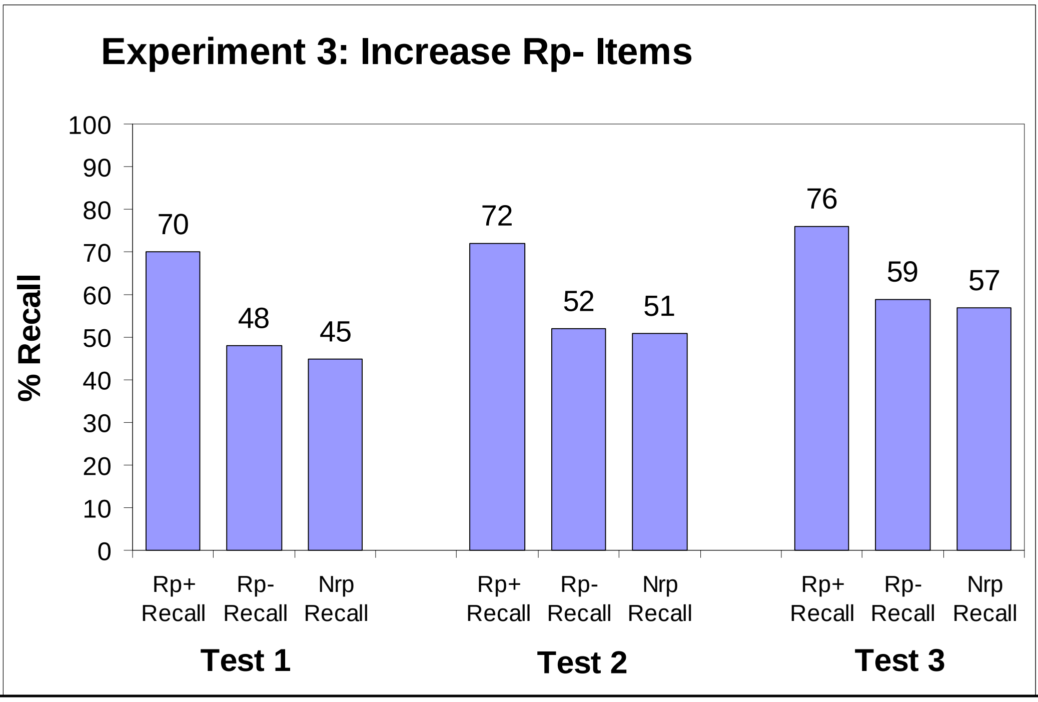

Figure 3.3 Behavioural results from Experiment 3. Each test produced facilitation effects, but no retrieval-induced forgetting. Recall performance improved with each test.

Differences between Experiments

A three-way repeated measures ANOVA was run with between-subject factor experiment (1, 2, or 3), and within-subject factors test (1^{st}, 2^{nd}, or 3^{rd}) and item type (Rp+, Rp-, or Nrp). There was not a significant main effect for experiment ($F(2, 89) = 1.23$, $p = .30$).

There was a significant main effect for test ($F(2, 178) = 80.58$, $p < .0001$, assumption of sphericity met $\chi^2(2) = 5.19$, $p > .05$), with no interaction for test and experiment ($F(4, 178) = .41$, $p = .80$). Contrasts showed significant differences between test 1 and test 2 ($F(1, 89) = 46.54$, $p < .0001$), and between test2 and test 3 ($F(1, 89) = 44.59$, $p < .0001$).These results indicate that participants' recall performance improved with each test, with improvements increasing steadily throughout the experiments (see Figure 3.4).

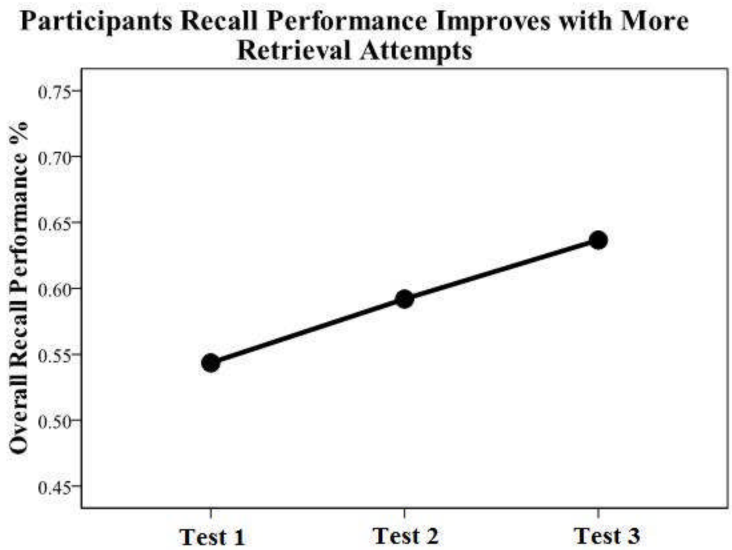

Figure 3.4 Differences between tests in overall recall (Rp+, Rp-, and Nrp items) for all three experiments. Each dot represents the mean score across experiments for overall recall.

There was also a significant main effect for item type ($F(1.92, 171.36) = 48.02$, $p < .0001$, Mauchly's assumption of sphericity was violated $\chi^2(2) = 7.68$, $p < .05$, therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (epsilon =.96)), but no significant interaction for item type and experiment ($F(3.86, 171.36) = 1.84$, $p = .13$). Contrasts showed a significant facilitation effect (difference between Rp+ and Nrp = $F(1,89) = 98.30$, $p < .0001$), but no overall effect of retrieval-induced forgetting (difference between Rp- and Nrp= $F(1, 89) = .044$, $p = .83$) (see Figure 3.5).

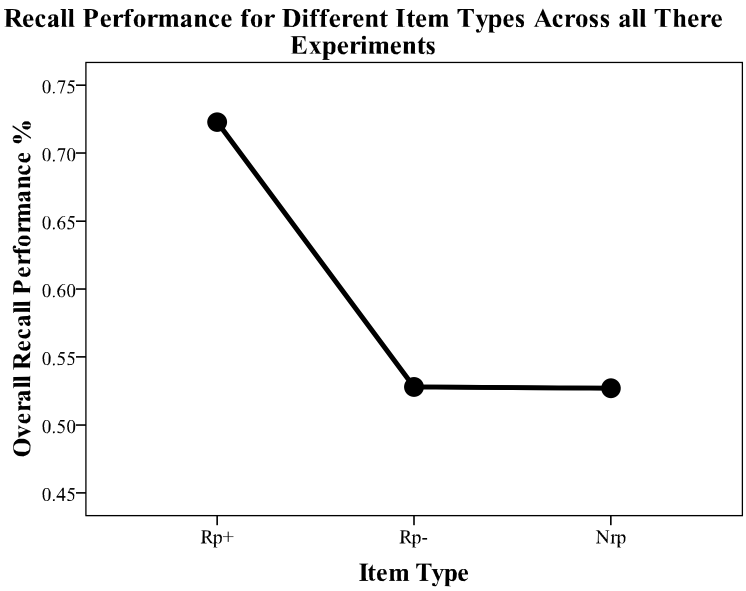

Figure 3.5 Differences between recall of the item types (Rp+, Rp-, and Nrp items) across the three experiments and tests.

Finally, there was a significant interaction between test and item type ($F(3.80, 337.74)= 4.00$, $p<.01$, Mauchly's assumption of sphericity was violated $\chi^2(9)= 23.82$, $p<.01$, therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (epsilon =.95)). Contrasts demonstrated that between Tests 1 and 2, the amount of facilitation (Rp+ minus Nrp) is larger ($F(1, 89)= 5.03$, $p<.050$) than between Tests 2 and 3 ($F(1, 89)= 1.73$, $p=.19$). These results show that as participants progressed from the first test to the last test, there were more improvements for recall of Rp- and Nrp words compared with Rp+ words.

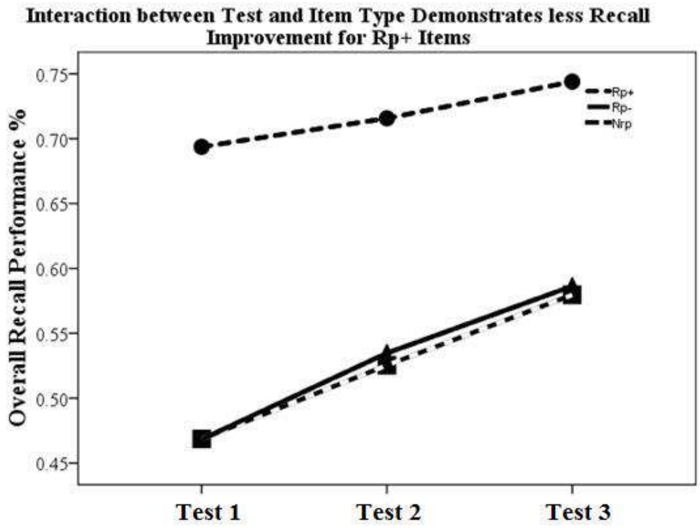

Figure 3.6 Each line represents the mean recall for a particular item type across all experiments. The slope of the lines illustrates the interaction between test and item type. Recall for Rp- and Nrp items improved more than Rp+ items as the tests continued.

EEG

Our analysis of event-recorded potentials (ERPs), revealed significant findings in all three phases of the resource allocation experiment. After an initial analysis and literature review, we chose two regions of interest, a frontocentral region (FC3, FCz, FC4), and a parietal region (P3, Pz, P4), to examine more closely. In imaging studies of RIF, authors have found significant differences in these specific regions at retrieval practice and test phases (Johansson, Aslan, Bauml, Gabel, & Mecklinger, 2007; Spitzer, Hanslmayr, Opitz, Mecklinger, & Bauml, 2009). Additionally, there are classic memory effects outside of the RIF literature, such as differential brain activity at study phase between words that are later remembered or not remembered, that have been shown to leave their electrophysiological signatures at these regions (Paller, McCarthy, & Wood, 1988; Rugg & Allan, 1999)

Study Phase

In the study phase, we recorded ERPs at the time of presentation of each word and then looked for differences between words that were later remembered or forgotten in the subsequent parts of the experiment. A word was classified as "remembered" if the participant recalled the word at least once throughout the retrieval practice phase or the test phase. Our results replicate a classic finding in EEG and memory related literature: ERPs in the study phase can predict memory performance on future recall tests. As observed in previous studies (Paller et al., 1988) we found that remembered items elicited ERPs in the parietal region that were more positive than ERPs for not-remembered words (see Figure 3.8). One way ANOVAs with factor remembered/not-remembered were run for each 50 millisecond (ms) time interval (for results, see Figure 3.7). These statistical analyses indicated that the observed differences in amplitudes (Figure 3.8) were significant from 350-600ms after the onset of the word.

Study Phase		
Differences between Remembered/Not-Remembered		
Time after Stimulus (ms)	Frontal	Parietal
0-50	1.46	0.17
50-100	5.79*	3.92(*)
100-150	1.32	0.93
150-200	4.39*	0.09
200-250	0.29	0.04
250-300	0.10	1.55
300-350	0.16	3.65(*)
350-400	0.37	**4.27***
400-450	0.32	**5.39***
450-500	0.87	**19.39*****
500-550	0.23	**15.22*****
550-600	0.89	**13.03*****

Figure 3.7 F-ratios for differences between amplitudes elicited by words that were later remembered or not-remembered. Significance is denoted by asterisks. Two or more significant differences together constitute a finding, and these findings are denoted in bold font.

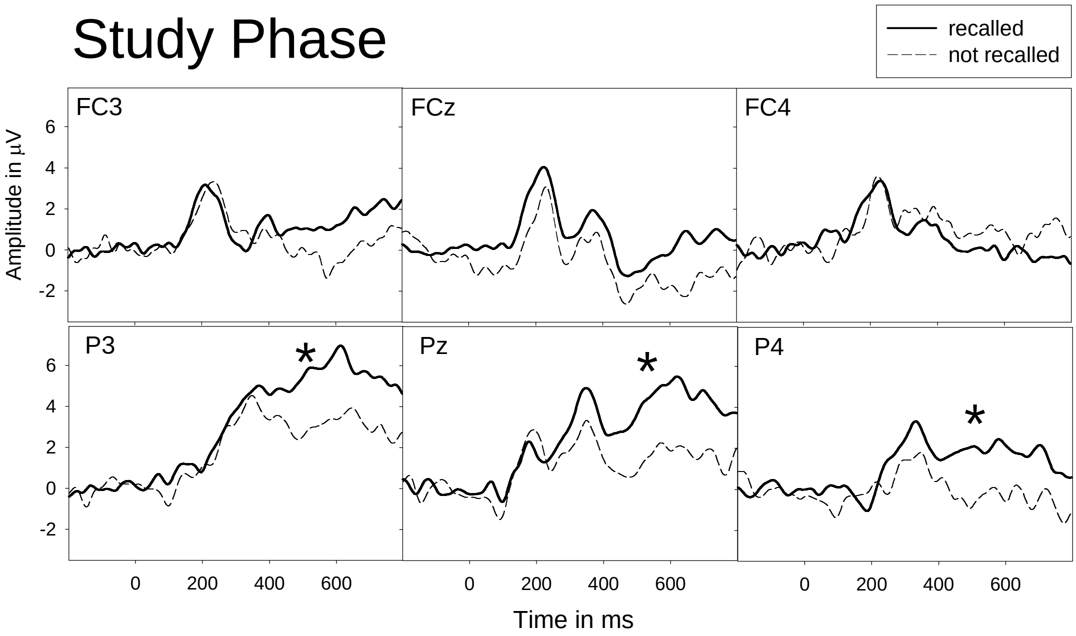

Figure 3.8 Recordings of ERPs during the study phase. Solid line represents amplitudes elicited after participant viewed words that they would later remember; dotted lines are for those that were not remembered. Asterisks indicate statistical significance.

Retrieval Practice Phase

As in the study phase, one way ANOVAs were conducted with the single factor of remembered/not-remembered. We found significant differences (see Figure 3.9) in the frontal region but none in the parietal (See Figure 3.10). In the frontal region, words that were successfully retrieved elicited less positive ERPs than not-remembered words. These differences were present from 150-400 ms after the word was presented; earlier than the parietal effects found in the study phase.

Retrieval Practice Phase		
Differences between Remembered/Not-Remembered		
Time after Stimulus (ms)	Frontal	Parietal
0-50	4.39*	0.26
50-100	3.29(*)	0.28
100-150	4.01(*)	0.01
150-200	**9.71****	0.02
200-250	**9.16****	0.04
250-300	**7.50***	0.03
300-350	**5.81***	0.02
350-400	**7.14***	0
400-450	3.45(*)	0.01
450-500	3.30(*)	0.83
500-550	2.75	4.03(*)
550-600	4.05(*)	2.8

Figure 3.9 F-ratios for differences between amplitudes elicited by words that were remembered or not-remembered. Significance is denoted by asterisks. Two or more significant differences together constitute a finding, and these findings are denoted in bold font.

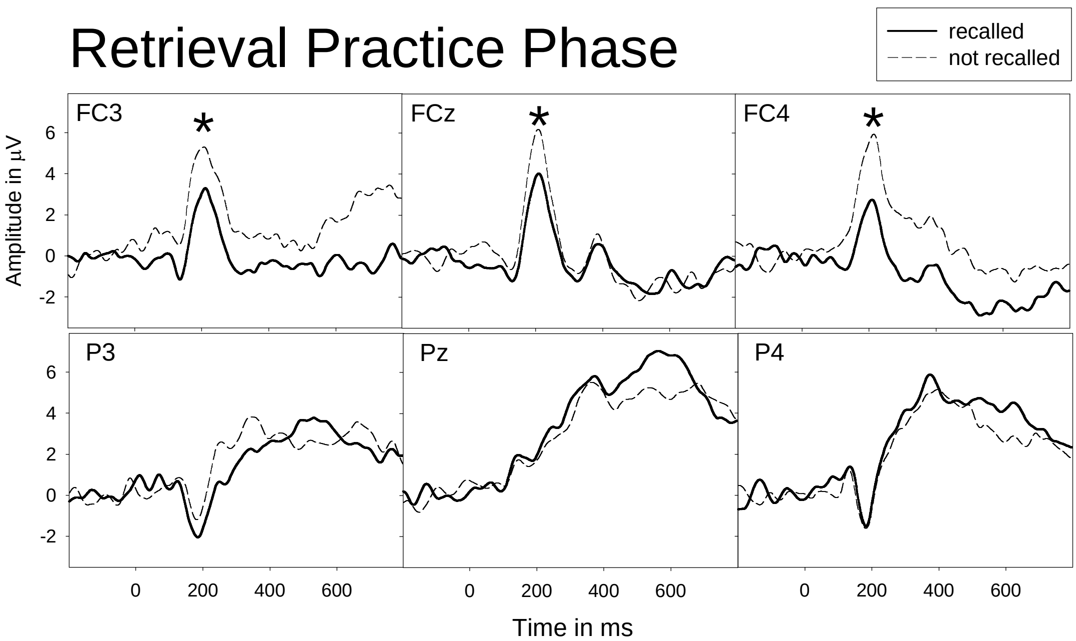

Figure 3.10 Recordings of ERPs during the retrieval practice phase. Solid line represents amplitudes elicited after participant viewed words that they would later remember; dotted lines are for those that were not remembered. Asterisks indicate statistical significance.

In the test phase, we looked at differences in amplitudes between words that were remembered and not-remembered, and also for differences in amplitudes between each item type. A two-way ANOVA was run with factors: memory (remembered or not-remembered) and item type (Rp+, Rp-, or Nrp). Each 50 ms-interval after word presentation was analyzed. Significant interactions ($F(2,32)=6.86$, $p<.01$) were found between memory and item type early (50-150ms) in the frontal recordings.

However, there were no significant findings between item types or between remembered/not-remembered items by themselves. Figure 3.11 demonstrates that for remembered words, the ERP recordings look similar regardless of item type.

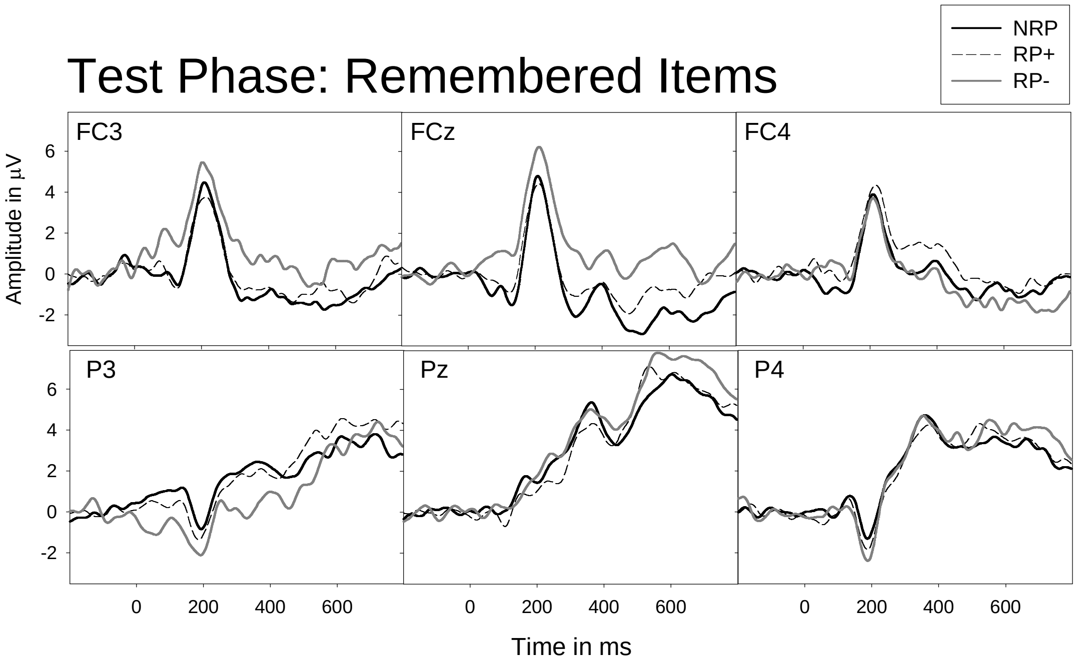

Figure 3.11 Recordings of ERPs during the test phase. The three lines represent amplitudes elicited for remembered words only, each line differentiates the amplitudes elicited for a specific word type. There were no significant differences between word type for the remembered words.

Analysis 2

The absence of significant findings could be due to lack of power and low signal to noise ratio. Some participants had to be excluded due to insufficient number of trials in each analysis, further decreasing power. For example, if participants remembered every word in one subgroup (e.g. all 5 Rp- items), then there were no data to compare remembered/not-remembered for that item type. For Rp- items, this happened with 7 participants. Likewise, one participant remembered all Nrp items and was therefore excluded from analyses involving that item type. After excluding such participants, we were left with 17 participants instead of the 24 that we had used for analyses in the study and retrieval practice phases. Therefore, data in the test phase were divided by item type and separate analyses ran with as many subjects as there were data for that particular item type. This optimized the power by giving us data from 24 participants for Rp+ items, 17 participants for Rp- items, and 23 participants for Nrp items. Significant differences emerged between remembered and not-remembered items in both the Rp- and Nrp item types (see Figure 3.12). These differences occurred early (50-200ms), right before the larger wave component. The large amplitude that follows this early effect mirrors amplitudes seen in the retrieval practice phase, with both occurring at around 200ms.

Test Phase- Frontal Regions Differences between Remembered/Not-Remembered			
# Participants →	24	17	23 participants
Time after Stimulus (ms)	Rp+	Rp-	Nrp
0-50	0.69	0.93	1.24
50-100	1.04	**9.00****	**6.17***
100-150	0.04	**5.04***	**6.08***
150-200	0.22	**7.9***	1.53
200-250	0.35	0.74	0.02
250-300	0.12	3.45(*)	0.3
300-350	0.01	0.08	0.363
350-400	0.16	0.02	1.76
400-450	0.07	0.65	0.65
450-500	0.07	0.53	0
500-550	0	0.2	0.18
550-600	0.06	0.88	0.42

Figure 3.12 F-ratios for differences between amplitudes elicited by words that were remembered or not-remembered for each particular item type (Rp+, Rp-, Nrp). Note statistical power varies by item type; the number of participants used in each analysis is given above the item type. Significance is denoted by asterisks. Two or more significant differences together constitute a finding, and these findings are denoted in bold font.

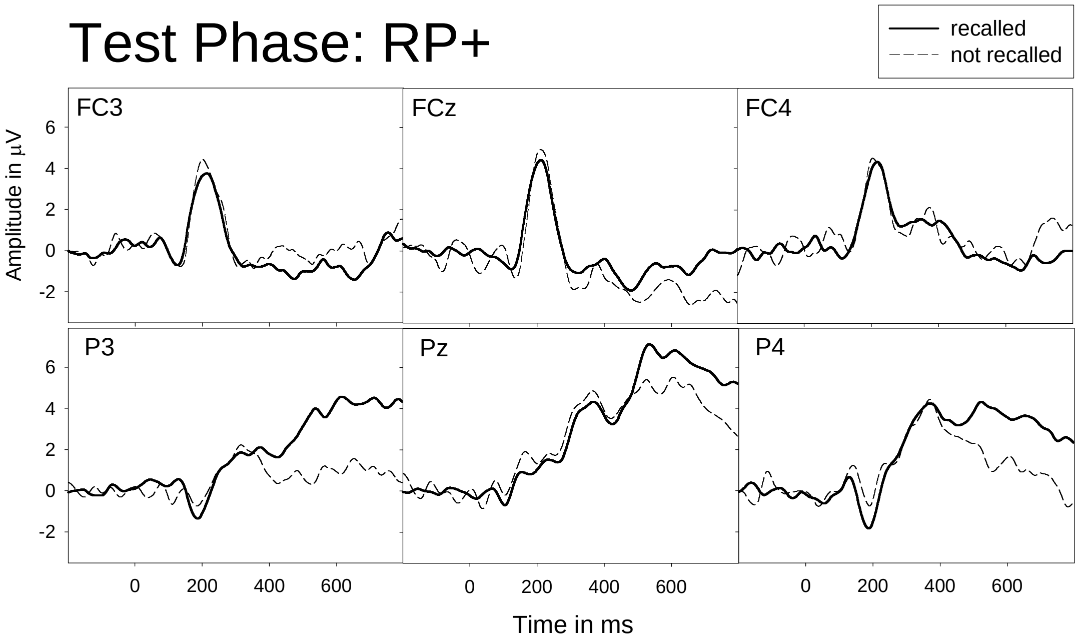

Figure 3.13 Recordings of ERPs during the test phase. Solid line represents amplitudes elicited after participants view Rp+ words that they would later remember, dotted lines are for those that were not remembered. Asterisks indicate differences of statistical significance.

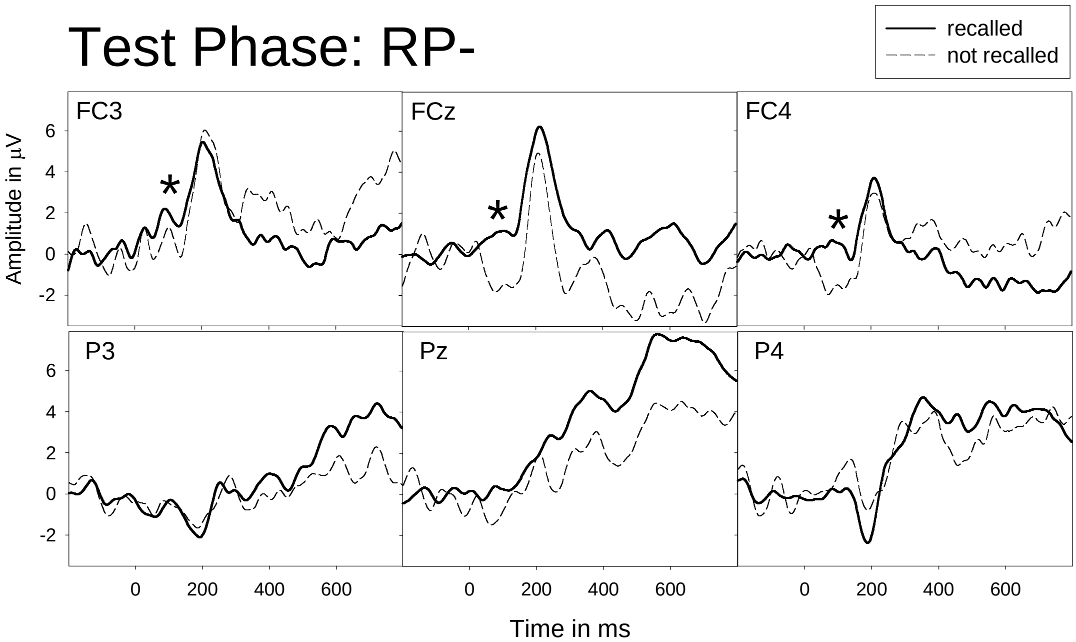

Figure 3.14 Recordings of ERPs during the test phase. Solid line represents amplitudes elicited after participants view Rp- words that they would later remember, dotted lines are for those that were not remembered. Asterisks indicate differences of statistical significance.

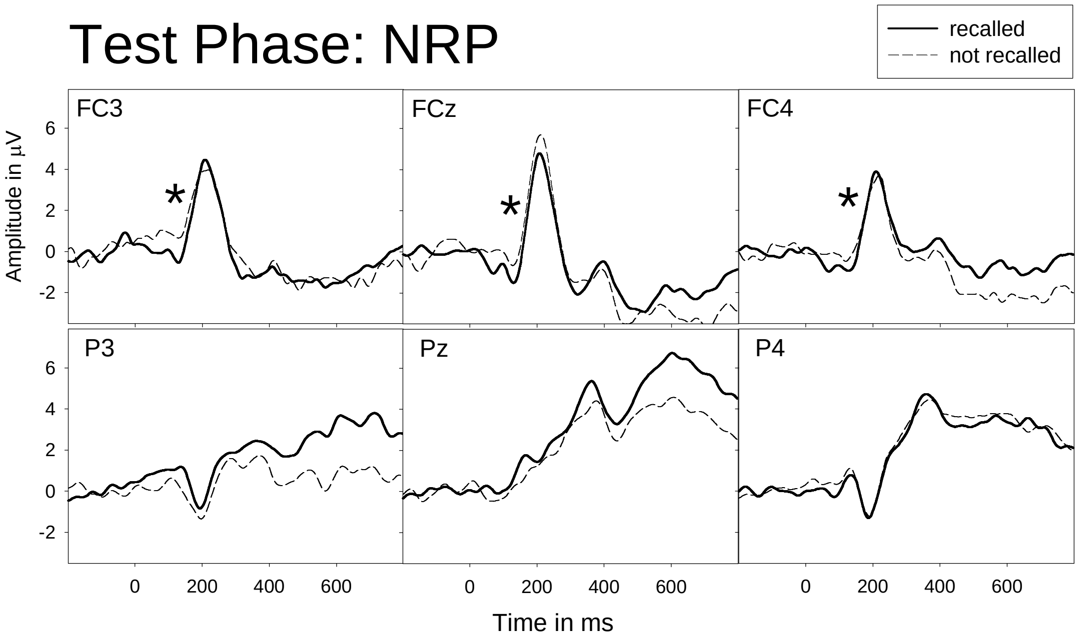

Figure 3.15 Recordings of ERPs during the test phase. Solid line represents amplitudes elicited after participants view Nrp words that they would later remember, dotted lines are for those that were not remembered. Asterisks indicate differences of statistical significance.

DISCUSSION

Behavioural Experiments

Summary

The present study was aimed at investigating a potential mechanism behind retrieval-induced forgetting that we have termed resource allocation. Three experiments were designed around the notion that increasing the number memories associated with one concept may reduce retrieval-induced forgetting by spreading out the limited resources available for that concept. In two experiments, we expanded the standard RIF paradigm by increasing the number of items in each category to 15 and varying the amount of Rp+ and Rp- items. We then compared these findings to a control; a standard RIF paradigm that contained 10 items in each category, with an equal number of Rp+ and Rp- items.

None of the three experiments produced significant retrieval-induced forgetting and there were no significant differences between experiments. However, all three experiments produced statistically significant facilitation effects for the practiced items when compared to the control items (Rp+ vs. Nrp items). Additionally, participants' recall performance significantly increased with repeated testing. Over the course of the three tests, participants' recall performance for Rp- and Nrp items improved more than recall for Rp+ items.

Differences between Item types

A standard retrieval practice paradigm usually produces two effects: facilitated recall for Rp+ items and impaired recall of Rp- items relative to an Nrp item baseline (Anderson, Bjork, & Bjork, 1994). In the present study, facilitation effects were evident in all three experiments. While the beneficial effects of retrieval practice are expected, what mechanism is responsible for producing them? This question deserves thorough examination because much of the debate surrounding the mechanisms responsible for RIF impairment revolves around whether or not the two behavioural effects are produced by the same mechanism. Thus, before we dissociate or amalgamate RIF impairments and facilitations, it is best to define the mechanisms behind facilitation.

One might suppose that retrieval attempts provide general practice that makes it easier to correctly retrieve items at test. This idea resembles performance facilitation where the familiarity with the task itself improves performance. Evidence to support this could include the finding that increasing the number of retrieval practice sessions significantly increases the magnitude of facilitation at final test for one study (Macrae & MacLeod, 1999)[3].

The results from the current study do not support this hypothesis. After the third test during test phase, Nrp items had undergone three retrieval attempts for each Nrp item; the equivalent number of retrieval attempts that Rp+ items had undergone in retrieval practice phase. However, the recall for Rp+ items at the end of retrieval practice (mean = 66%) is significantly higher than the recall for Nrp items after three

[3] Although we did not replicate this finding in the present study, the number of Rp+ items varied in each experiment, which may have contributing influence on the facilitation effects.

tests in the test phase when Nrp recall has reached it's highest (mean = 39%). If facilitation effects were due to a familiarity with the retrieval task procedure, then one could have expected recall performance for Nrp and Rp+ items to be similar as each item had undergone the same number of retrieval attempts. This was not the case in this study. However, our results alone are insufficient to characterize the mechanism responsible for our observed facilitation effects.

As an alternative hypothesis to the one described above, Carrier and Pashler (1992) argued that the benefits of retrieval on later recall performance occurs at the level of the item either by strengthening existing connections or by creating new connections which then increase the likelihood of the item being recalled. Their study compared retrieval practice to extra study and demonstrated that retrieval practice significantly improved memory performance over extra study exposures of the same material (Carrier & Pashler, 1992).

Having recorded ERPs during the retrieval practice phase, the current study may provide a window into the neural correlates of the facilitation process. Unlike other imaging studies that have monitored brain activity during retrieval practice phase, we were the first to report ERP differences between Rp+ items that were later remembered (facilitated) versus those that were not remembered. Our results showed that Rp+ items that were successfully retrieved elicited significantly less positive ERPs than not-remembered words. These differences were present from 150-400 ms after the word was presented. Furthermore, a similar frontal component appeared in the test phase for all three item types. Despite behavioural differences between Rp+ and Nrp items after each item type had received three retrieval attempts, the imaging results do not suggest that there is a mechanism other than those required for selective recall behind facilitation effects. Other factors such as retention interval (only Rp+ items undergo retrieval immediately after study), order (retrieval practice requires that Rp+ items are retrieved first), or load (Rp+ items are recalled amongst themselves rather than amongst 20 other items) may help facilitate the retrieval of Rp+ items, but it appears that the underlying mechanism does not differ electrophysiologically from other instances of selective retrieval.

In addition to facilitation, we found that recall for Rp- items and Nrp items improved significantly more than recall for Rp+ items. This significant difference is more likely attributed to ceiling effects for the Rp+ items rather than a meaningful difference in recall improvements between item types.

Absence of RIF

Unfortunately, none of the three experiments produced retrieval-induced forgetting effects. As mentioned previously, we do not believe that the absence of retrieval-induced forgetting effects in any of our conditions was due to lack of power. RIF effects are robust and several studies have found statistically reliable RIF effects with fewer participants than our smallest condition (n = 24).

Additionally, it is unlikely that the construct of our paradigm prevented us from producing RIF effects. The procedures for the first experiment were designed according to other paradigms used in the RIF literature (with two exceptions discussed later). Specifically, the arrangement of the materials, two novel categories of 10 items each (5 Rp+, Rp-, 10 Nrp), came from a recent study that also used two fictitious planets and produced retrieval-induced forgetting (MacLeod, Saunders, & Chalmers, 2010). The timing of the presentation of stimuli, and other procedural details were also similar to another study that produced RIF (Johansson, Aslan, Bauml, Gabel, & Mecklinger, 2007). Therefore there was no manipulation or obvious difference in our standard RIF procedure that we could readily attribute to the lack of retrieval-induced forgetting. Ruling out statistical power and experimental design, it is most likely that the modifications that we made to specific items in materials prevented participants from producing RIF effects.

There was large variability in the memorability scores for each word (see Appendix B). Even though memorability was balanced between subsets, some studies have suggested that RIF may occur at the level of the item. In a recent model put forth to account for the mechanisms behind RIF, authors argued that inhibition works selectively to weaken only specific items that are threatening to displace Rp+ items (Norman, Newman, & Detre, 2007). The model predicts each item receives a certain amount of excitatory output that could be based on difficulty/memorability of word, personal relevance, etc. During retrieval practice, inhibition fluctuates to identify the excitatory outputs for each item in order to selectively strengthen weak Rp+ items or weaken Rp+ competitors. However, words that are extremely strong or weak will fall outside the range of exploratory fluctuations of inhibition and remain unaffected. For example, if a Rp+ word is very strong, an and Rp- word very weak, RIF will not occur because the Rp- item does not incite enough competition to elicit inhibition; the Rp+ word is so strong that it will be recalled regardless of whether the Rp- word is inhibited or not. Anderson *et al's* experiment (1994) demonstrated that this is true. Likewise, Rp- items that are very strong may be impervious to RIF effects because they also fall outside the range of fluctuation; it will be remembered regardless of Rp+ strength. Anderson's inhibitory theory does not explicitly predict this, however, the fact that Rp- items are remembered at all would suggest that some Rp- items do squeak past inhibition and are successfully retrieved.

In the current study, we found variation in memorability at the level of the item; regardless of item assignment (Rp+, Rp-, or Nrp), some words were recalled better than others, while other words were recalled barely at all (even as Rp+ items). Therefore, a post-hoc analysis was done on Experiment 1, the standard retrieval practice paradigm, to test the predictions of the Norman *et al.* model. Memorability scores were recalculated to include all of the data gathered in all three experiments. The strongest items (memorability score over 50), and the weakest items (memorability score under 10) were removed from the data in Experiment 1 and statistical analyses were rerun. With this post-hoc evaluation, RIF effects were evident in the first and second tests of test phase ($p = .024$ and .026 respectively), but not in the third ($p = .09$). These results demonstrate that even though our subsets were balanced for memorability, the variable difficulty of each particular word may have created a scenario in which competition was too high/low to effectively inhibit Rp- items. The results also provide support for the notion that inhibition works selectively, and that the variations in each item's difficulty may account for the absence of RIF in the current study.

Integration effects provide another possible explanation for the absence of RIF. Experiment 1 was run last, and after finding no RIF in the other two experiments, we began to question participants about their memory strategy immediately after their completion of test phase. Twenty-five out of the twenty-nine participants that were asked reported making associations between the study words. Some of these associations involved visual imagery ("Rupple was the lobby of the psychology building and Minosco was the physics department. I pictured all of the items in each room"), and others sequential order. The most reported associations were semantic ("<u>squirrels</u> <u>skiing</u> down a <u>volcano</u> wearing <u>tartan</u>" and for Rupple, "the <u>French</u> have no <u>brains</u> and eat lots of <u>chocolate</u>"). Spontaneously organizing the study words into sentences would be likely mental strategies because that is how the participants studied each word (e.g. THE SKY IN MINOSCO IS <u>TURQUOISE</u>). But then why was the study from which we based our paradigm able to produce RIF effects, and we were not?

Beyond materials, the current study differed from that of MacLeod *et al*. (2010) in two ways; participants studied each item three times (MacLeod et al., 2010) instead of one (current study), and 2) participants were given the original sentence as a retrieval cue (MacLeod et al., 2010) instead of just the planet name (MINOSCO-TU____) in the current study to reduce motor artifact in EEG study). These changes made our paradigm considerably more difficult which is evident by the varying rates in recall performance between the two studies. In MacLeod *et al.* (2010), participants averaged 87% recall for Rp+ words, 60% for Rp- words, and 73% for Nrp items. The overall recall performance for the three experiments study was comparatively lower (73%, 53%, 52%, respectively), and 19 participants out of 111 (17%) were excluded for not meeting minimum recall performance criteria. Perhaps because participants were warned of the difficulty of this task ("Make sure you pay attention during study phase, because you only see each word one time"), they put forth extra effort to remember by using integrative-retrieval strategies. The participants who did report using other retrieval strategies (e.g. rehearsal), reported switching to integrative strategies because the study phase task became too difficult. Beyond this issue of difficulty and the differences in our materials mentioned above, there are no other variations from the MacLeod *et al.* (2010) study that could explain the absence of retrieval-induced forgetting in the current study.

The fact that none of our experiments produced RIF is an interesting finding in itself. In studies that do find RIF, the effect is robust. The current standard retrieval practice paradigm experiment (Experiment 1) only slightly modified the materials from a previous study that did produce RIF (MacLeod et al., 2010). What does this variation in findings tell us about the mechanism behind RIF? Strong items were remembered regardless of their item assignment (Rp+, Rp-, or Nrp). Anderson's inhibition theory would predict that these strong items would be more likely to be inhibited as Rp- items because of the competition that they impose on Rp+ items. Since this was not the case, our findings are more consistent with the Norman *et al.* model which places emphasis on individual items.

In addition to the mechanism, what does the absence of RIF in this study tell us about the generalizability of the phenomenon? If RIF is regulated by inhibitory mechanisms, perhaps RIF is not as reliable a measure of inhibition as people might think. Other studies have found that RIF effects are insensitive to age (Hogge, Adam, & Collette, 2008), and illnesses that have been known to affect inhibitory control (Moulin et al., 2002). Even amongst healthy young adults whose inhibition we would to be intact, RIF effects are variable. In Johansson *et al.*'s study (2007), authors conducted a post-hoc analysis by diving their participants into a "high-forgetting" and "low-forgetting" group. While both groups demonstrated significant facilitation effects, the low forgetting group did not produce a significant retrieval-induced forgetting effect. The participants were of the same age group and underwent the same experimental paradigm. How can we account for this variation amongst individuals? Why do some people seem vulnerable to RIF effects and others not? Whatever the case may be, the absence of RIF in the present study demonstrates how much we still have much to learn about the phenomenon and that it may not be as simple or generalizable as it seems.

Improvements in Recall Performance

The results of the current study demonstrated that participants' recall performance improved with subsequent recall tests. These improvements are characteristic of a memory phenomenon known as hypermnesia. Generally, when participants are subjected to repeat testing, they remember information that they could not remember in previous tests, but also forget other material. These effects cancel out so that there is generally no overall increase in recall despite multiple testing on the same material. Under certain circumstances, however, participants demonstrate hypermnesia, or significant improvements in recall performance.

While it has been suggested that hypermnesia occurs when information is remembered in an "imaginal code," Roediger (1982) argues that hypermnesia is caused by repeated retrieval practice. He suggests that each time the memory is retrieved, the organization of that item in memory improves. He believes that this optimized organization, and not the strengthening of memory traces over time, is the mechanism responsible for hypermnesia. From the current study, we know that materials in the standard RIF paradigm are vulnerable to hyperamnesic effects. It would be interesting then, to examine retrieval-induced forgetting after repeated test phases. According to inhibition theory, recall for Rp- items would decrease or stay the same, as long as all repeat testing occurred within 20 minutes of the initial test. However, if recall performance for Rp- items did improve, it may provide evidence in support of a strategy disruption hypothesis. Beyond the theoretical implications, it is important to note that the standard RIF paradigm is subject to hypermnesia and is a worthwhile topic for further investigation. If it is the case that inhibited Rp- items are also subject to hypermnesia, repeated retrieval tests may provide another boundary condition that could be exploited in scenarios where the detrimental effects of RIF are undesirable (e.g. eyewitness testimony).

EEG

Study Phase

During the study phase, participants are presumably encoding and storing study material into long-term memory. Our imaging results indicate differential brain activity at this time for words that are later remembered or not-remembered, and therefore may reflect differences in encoding. The significant differences were evident in the parietal region 350-600 ms after the presentation of the word. Words that were later remembered elicited more positive ERPs. These differences are congruent with previous studies (Paller et al., 1988) that found more positive ERPs 400-500 ms after the presentation of words that were later remembered on the same regions of interest used in the current study (see Figure 4.1 for comparison). Ratings completed by participants after the recordings in Paller *et al.* (1988) indicated that words rated as being “interesting” were significantly better remembered than those rated as “uninteresting.” The authors suggested that these reported differences might have influenced processing by either encoding representations specific to each word or by differentially encoding due to fluctuations in arousal (nonspecific). Whether this is the case and differential encoding predicts the behavioural differences, or whether differential rehearsal produces the larger amplitudes for later-recalled items, the current study demonstrates that there are differences in brain activity upon presentation of the material at study phase. The fact that we were able to reproduce this classic finding validates the imaging component of the present study (e.g. our study did have enough power to produce significant findings), and suggests that participants differentially encoded or stored the study material.

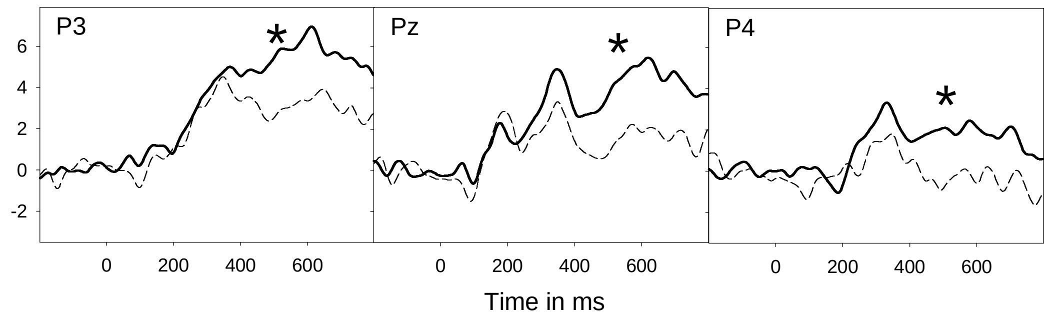

Figure 4.1 The parietal ERPs in our study phase (above) and resemble those in Paller *et al.* (1988). Solid lines indicate ERPs elicited from words that were later remembered; dotted lines form those that were not remembered. Items that are later remembered elicit more positive ERPs from 400-700 ms.

Retrieval Practice Phase

During retrieval practice, we found statistically different amplitudes for words that were later remembered versus those that were not remembered. Words that were later remembered elicited less positive ERPs from 150-400 ms in the frontal region. Johansson *et al.* (2007) also recorded ERPs during retrieval practice condition. Although they compared retrieval versus relearning conditions rather than items that were later remembered or not remembered, their ERP findings for their retrieval condition resemble those of the current study. The authors found that during retrieval practice, presentation of retrieval cues elicited positive-going ERP amplitudes at around 200 ms in the frontal regions. This wave form was statistically significant from those elicited by the representation of study items in the relearning condition. In addition, there were two time windows (300-400 ms and 1000-2000 ms), in which the ERPs in the anterior frontal region were predictive of RIF. The authors found their findings supportive of Anderson’s inhibition theory on the basis that 1) the anterior frontal ERP waveforms were predictive of RIF, 2) these predictive ERPs occurred during retrieval practice phase when Anderson predicts that inhibition takes place, and 3) that the differences were found in regions of interest (prefrontal and frontal) that other studies have concluded to be crucial to the control of competitor memory traces during memory retrieval.

In light of the present study, it could be argued that the findings of Johansson *et al.* (2007) highlight differences between selective retrieval and extra study. The wave component that we found during retrieval practice phase resembles their frontal wave components in amplitude size, in time it appears after stimulus onset, and in its region of the brain (see Figure 4.3). Unlike Johansson *et al*., however, our behavioural results did not show evidence of retrieval-induced forgetting. Due to the fact that retrieval practice elicited similar ERPs without producing RIF, it is likely that these amplitudes reflect the processes of selective retrieval rather than inhibition of Rp-items.

In Johansson *et al.*, anterior frontal ERPs in the retrieval condition were predictive of RIF, but the retrieval condition itself was predictive of RIF. Their argument would be more convincing if these electrophysiological differences still emerged when there were no behavioural differences between conditions. Furthermore, we found similar frontal ERPs at test phase, where Johansson *et al.* did not record, which provide more evidence to suggest that the early positive components described in this study and in Johansson *et al.* reflect selective retrieval and not inhibition (discussed further in Test Phase).

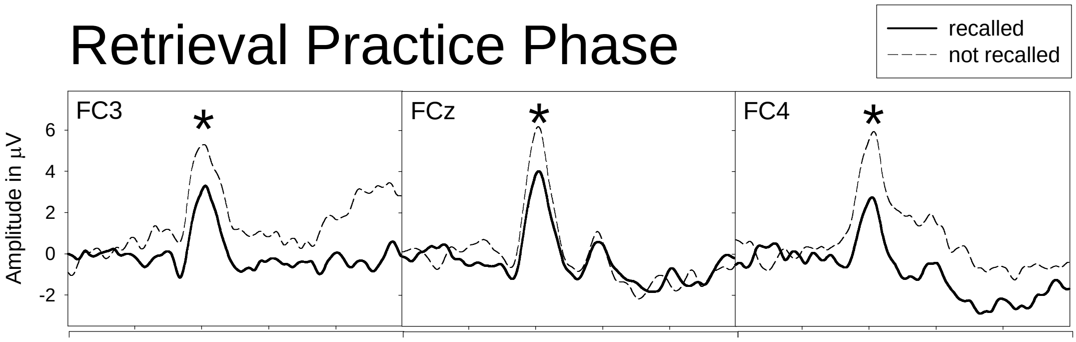

Figure 4.3 ERPs in the current study resemble those from Johansson *et al.* (2007). In both the present study and in Johansson *et al.,* the positive-going ERPs begin between 250-300 ms after

In the intentional forgetting literature, authors have often attributed anterior prefrontal, or frontal activations to inhibitory control (Hanslmayr et al., 2008; Kuhl, Dudukovic, Kahn, & Wagner, 2007; Wimber, Rutschmann, Greenlee, & Bauml, 2009). However, these regions have been shown to play roles in executive processing other than inhibition. Iidaka *et al.* (2006), for example, used both fMRI and ERP data to monitor brain activity while participants performed a recognition task. They argued that during recollection (which they distinguish from familiarity), the following functional network is activated: parietal area (inferior parietal lobule) connects bilaterally to the posterior prefrontal cortex which then connects unilaterally to a network of frontal cortices (anterior prefrontal, ventral prefrontal, and medial prefrontal). Their findings are significant because their behavioural task activated the same regions that are activated during RIF paradigms (Kuhl et al., 2007; Wimber et al., 2009), but without any behaviourally induced competition.

In addition to generating activity in the same brain regions, other studies have produced similar types of activity in retrieval tasks that presumably do not involve inhibition. For example, studies have recorded ERPs while participants were engaged in explicit (vs. implicit) retrieval tasks and found components similar to the one elicited in the retrieval practice phase of the current Experiment 2. The wave components produced by explicit selective retrieval are marked by positive going ERP that onsets at around 300 ms post-stimulus (Rugg & Allan, 1999, in their paper see Figure 56.8). Other explicit retrieval studies have shown activations in these same anterior prefrontal regions with fMRI (Buckner & Koutstaal, 1998). In these studies of explicit retrieval, there are no competitors as there are in RIF paradigms. Participants are given cues and asked to retrieve the words that they previously studied. Mixed in with the cues from previously studied words are novel words that participants have not seen. There is no theoretical reason that this experimental design would invoke the type of competition that takes place in RIF, yet the task elicits similar ERP data. Therefore, such studies provide additional evidence that the components observed during retrieval practice in this experiment and in other ERP studies of RIF may be caused by the act of *selective retrieval* and not necessarily by the inhibition of competitor items.

Test Phase

In the first statistical analysis, we reported a significant interaction in ERPs recorded at test phase between item type and whether the item was remembered or not remembered. This occurred early (50-150 ms) in the frontal regions. Although we would anticipate a difference in ERPs between remembered and not remembered words, we did not find any significant differences. Also unexpected was the absence of significant findings between item types to reflect the differences in behavioural data (facilitation effects). These results may be attributed to a reduction in power. The fact that both study and retrieval practice phases produced significantly different ERPs for remembered/not-remembered words demonstrates the sufficiency of using 24 subjects for the imaging component of this experiment. In the test phase, however, some of the subjects were excluded due to insufficient trials (e.g. they remembered all Rp- words), leaving just 17 subjects for this analysis. It appears that this decrease in power was sufficient to occlude any significant findings.

In the second analysis, the data were divided by item type in an effort to optimize power. This analysis revealed significant differences between remembered and not-remembered words for Rp- and Nrp words. These differences occur just before the wave component, with the activity being more positive for the remembered Rp- items but the opposite way around for remembered Nrp items. Furthermore, these differences appeared rather early (50-150 ms), and therefore may reflect motor artifact from participants' early responses to retrieval cues viewed for the first time. If this were the case, it is logical that Rp+ cues did not elicit these early differences, because participants were already familiar with the Rp+ cues through retrieval practice and could appropriately wait to respond. In any case, the signal to noise ratio would need to be improved before definitive conclusions could be made from this second analysis.

Even though the statistical power was too reduced to produce significant findings between items, we can still examine the ERPs themselves. Figure 3.11 illustrates a positive-going ERP in the frontal region that resembles those found in the retrieval practice phase. This finding provides further evidence for the proposal made earlier that this wave component reflects selective retrieval.

Parietal Effects

In the current study, we found no significant differences in the parietal region after the study phase. Much of the literature regarding imaging memory retrieval, however, discusses the vital engagement of the parietal cortices in the successful recollection of specific memories. Wagner *et al.* (2005), for instance, summarized findings from several fMRI studies that describe activity in parietal regions during episodic retrieval tasks. They found repeatedly that multiple posterior parietal regions are active during episodic retrieval, even if participants are falsely ‘recognizing’ new items or inaccurately recalling an event (Wagner, Shannon, Kahn, & Buckner, 2005). Likewise, Think/ no-think and RIF studies have found late parietal positivities associated with retrieval attempts (Mecklinger, Parra, & Waldhauser, 2009; Spitzer, Hanslmayr, Opitz, Mecklinger, & Bauml, 2009). Iidaka et al.’s proposed model suggests that a frontoparietal network of regions assists us in recalling memories.

Conclusions

The current study was aimed at exploring the neural correlates of retrieval-induced forgetting. All three experiments produced significant facilitation effects, but did not produce retrieval-induced forgetting. We believe this absence of RIF may be due to variability in the memorability/difficulty of the chosen materials. Having failed to produce a RIF effect, we cannot speculate further on the possible mechanism. However, we do argue against the conclusions of previous studies that have attributed certain frontal ERP activity during retrieval phase to inhibition. Our imaging data suggests that similar brain activity occurs in retrieval practice and at test phase. Since this characteristic activity was present in the current study when RIF was not, we conclude that such activity likely reflects the selective retrieval of episodic memories.

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Appendix A.

Materials were taken from MacLeod *et al.* (2010), and consisted of information that described two fictitious planets. First, we added 6 additional words and sentences to the materials from MacLeod *et al*. (Figure I) so that we could have 15 items in each category rather than 12 (additions are highlighted in bold in Figure II). Then we filled some of the original sentences with new words so that each word began with a unique pair of letters. Finally, we swapped the materials in each planet in to balance each list for word length and word frequency (Francis, Kučera, & Mackie, 1982). A pilot study demonstrated that participants showed differential performance for the two lists (see Appendix B), so the sentences were swapped a second time giving us the final list that we used in the current study (Figure II).

Cue/ Categoy	Item
Minoscoswell	
The official language spoken on Minocoswell is Latin	Latin
Minocoswell has a large variety of amphibian species	amphibian
The largest building on Minocoswell is the cathedral	cathedral
The Minocoswell flag has a tartan pattern on it	tartan
The main cause of death on Minocoswell is obesity	obesity
The main atmospheric gas on Minocoswell is helium	helium
Minocoswell is shaped like an octagon	octagon
The houses on Minocoswell all face the setting sun	sun
Minocoswell's most abundant mineral is diamond	diamond
The most common tree on Minocoswell is the sycamore	sycamore
The clarinet is played in church on Minocoswell	clarinet
The sky in Minocoswell is turquoise	turquoise
Rupplenair	
One of the staple foods on Rupplenair is pumpkin	pumpkin
The main occupation on Rupplenair is gardening	gardening
Ferrets are a sacred animal on Rupplenair	ferrets
Rupplenair@s main mode of transport is the tram	tram
The creatures living on Rupplenair always wear gloves	gloves
The most popular drink on Rupplenair is sherry	sherry
Pistachio is the most popular ice cream flavour on Rupplenair	pistachio
Clothes on Rupplenair are made of silk	silk
Rupplenair has a rainforest climate	rainforest
The newest electrical appliance on Rupplenair is the toaster	toaster
It is possible to communicate on Rupplenair via the Internet	internet
Rupplenair is made from very old volcanoes	volcanoes

Figure I. Original materials taken from MacLeod *et al.* Items were studied and retrieved with their respective sentences.

Cue/ Category	Item
Minosco	
The houses on Minosco all face NORTH	north
The traditional dance of Minosco is the WALTZ	waltz
The Minosco flag is covered with TARTAN	tartan
People of Minosco use their mountains for SKIING	**skiing**
The most sacred animals on Minosco are SQUIRRELS	squirrels
Most popular type of theatre in Minosco is DRAMA	**drama**
People of Minosco like to fish in the RIVERS	**rivers**
One of the staple foods on Minosco is PUMPKIN	pumpkin
Minosco is made from very old VOLCANOS	volcanos
The main cause of death on Minosco is OBESITY	obesity
Minosco looks like a RECTANGLE	rectangle
Clothes on Minosco are made of SILK	silk
The most popular drink on Minosco is JUICE	juice
Minosco's most abundant mineral is DIAMOND	diamond
Inhabitants of Minosco like to play the VIOLIN	violin
Rupple	
It is only possible to communicate on Rupple via WRITING	writing
The largest structure on Rupple is the CATHEDRAL	cathedral
People of Rupple decorate their homes with ROSES	**roses**
The sky in Rupple is TURQUOISE	turquoise
The creatures on Rupple always wear GLOVES	gloves
The official language spoken in Rupple is FRENCH	French
The climate in Rupple is TROPICAL	tropical
The most common tree on Rupple is the WILLOW	willow
Everyone on Rupple owns a BICYCLE	**bicycle**
The majority of species on Rupple are MOTHS	**moths**
Creatures from Rupple have multiple BRAINS	brains
People on Rupple cook with a STOVE	stove
The main atmospheric gas on Rupple is HELIUM	helium
The most common flavor of ice cream on Rupple is CHOCOLATE	chocolate
The main occupation on Minosco is GARDENING	gardening

Figure II. Materials for all three experiments. Shown above are the sentences that were given in study phase, with the study words presented in all capital letters.

Appendix B.

The pilot study determined that the difficulty of each list was unequal. The data from these 37 participants was then used to calculate a memorability score by calculating the frequency with which a word was recalled when it was an Nrp item. Each item's Nrp frequency, or memorability score, was taken into account with it's length and frequency in the English language to create the final two lists (Figure II). When having to compromise on one of these three criteria in dividing the lists into subcategories, memorability score was given priority because it was a better predictor of difficulty. Words in every subcategory averaged between 6-7 characters in length (see Figure III). Word frequency was based off of the data collected in Francis *et al.* (1982).

Another short pilot experiment was run (12 participants) to test the new lists of materials. This second pilot experiment and found that the memorability scores remained consistent for each item despite their new arrangement. At this point, we began running participants for the current study.

Sub-categories	Memorabilty	Memor-ability average	Planet Memor-ability average	#letters	letter average	Planet letter average	word frequency	word freq. average	Planet freq. average
M1									
north	4	6.6		5	6.2		63	13.4	
waltz	3			5.0			1.0		
tartan	9			6.0			0.0		
skiing	10.5			6.0			2.0		
squirrels	6.5			9.0			1.0		
M2									
drama	6	6.3		5.0	6.6		43.0	13.2	
rivers	3			6.0			15.0		
pumpkin	1.5		6.47	7.00		6.33	2.00		12.73
volcanos	8			8.00			1.00		
obesity	13			7.00			5.00		
M3									
rectangle	1.5	6.5		9.00	6.2		15.00	11.6	
silk	4.5			4.00			13.00		
juice	11.5			5.00			11.00		
diamond	6.5			7.00			8.00		
violin	8.5			6.00			11.00		

Sub-categories	Memorability	Memor-ability average	Planet Memor-ability average	#letters	letter average	Planet letter average	word frequency	word freq. average	Planet freq. average
R1		mem avg.			letter avg.			freq. avg.	
writing	10.5	6.4		7.00	7.2		37.00	11.8	
cathedral	3.5			9.00			8.00		
roses	5			5.00			7.00		
turquoise	4.5			9.00			1.00		
gloves	8.5			6.00			6.00		
R2									
French	13	6.4		6.00	6.4		32.00	11.6	
tropical	3			8.00			11.00		
willow	4		6.43	6.00		6.93	8.00		11.87
bicycle	5.5			7.0			5.0		
moths	6.5			5.0			2.0		
R3									
brains	5.5	6.5		6.0	7.2		18.0	12.2	
stove	5			5.0			17.0		
helium	12.5			7.0			15.0		
chocolate	2.5			9.0			9.0		
gardening	7			9.0			2.0		

Figure III. Planets were sorted into 3 subcategories that remained the same throughout the three experiments. Different combinations of subcategories were formed to make different groups of Rp+ items. Memorability score reflects an item's frequency as an Nrp item. Words in every subcategory averaged between 6-7 characters in length. Word frequency was based off of the data collected in Francis *et al.* (1982).