Memory Control:
Investigating the Consequences and Mechanisms of
Directed Forgetting in Working Memory

by

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Dedication

To my family.

Thank you for all of your love, support, and encouragement!

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Abstract

Can people control what they remember and what they forget? Directed forgetting is an experimental method for investigating this question. Prior research has most commonly studied directed forgetting in a long-term memory context using long lists (i.e., greater than 6 items) and test delays of minutes or hours. My dissertation steps outside this standard paradigm and examines directed forgetting within working memory, when forgetting is performed on memory representations that are currently held in mind, potentially allowing for more targeted control. My dissertation has two main research aims: (1) to document the effectiveness of directed forgetting implemented within working memory using explicit long-term memory tests and implicit measures of semantic and proactive interference, and (2) to examine the role of rehearsal in directed forgetting within working memory. Results demonstrated that people could voluntarily forget specific memoranda within a canonical working memory task, and that this forgetting diminished both semantic and proactive interference and reduced the long-term memorability of these items. Moreover, additional experimental evidence indicated that articulatory suppression interfered with directed forgetting and that forgetting could be performed in isolation, without the presence of competitors to remember. In combination, these experiments suggest that directed forgetting within working memory attenuates the strength of the to-be-forgotten memory representations, that it requires an active control process that is limited by articulatory suppression, and that it can be performed efficiently regardless of whether or not additional to-be-remembered items are present. This research

expands our knowledge of whether and how people can voluntarily control the contents of memory by further characterizing the consequences and mechanisms of directed forgetting within working memory.

Chapter 1: Introduction

The ability to control the contents of memory can be useful and adaptive. Memory control can be used to prioritize favorable or important memories and to forget adverse or unimportant memories. For instance, individuals may wish to remember positively valenced information (i.e., personal compliments they received) and crucial details (i.e., deadlines and requirements for important projects). On the other hand, people may be motivated to forget negatively valenced information (i.e., details of traumatic experiences) or unimportant knowledge that they are unlikely to be asked to remember in the future. Such intentional control over memory has received substantial interest, and a variety of methods to exert memory control have been explored. Prior research has focused on techniques like retrieval suppression of previously well-learned memories (e.g., Anderson & Green, 2001; Anderson & Huddleston, 2012) and controlling the contents of long-term memory with directed forgetting instructions (e.g., Bjork, 1972; MacLeod, 1975).

In contrast, my dissertation focuses on the voluntary control of memory representations that are actively held in mind in working memory, assessing the effectiveness of this form of memory control and examining several possible mechanisms for its implementation. Here, I provide a brief introduction to the topic of directed forgetting and memory control and summarize the experiments included in my dissertation. Within each chapter an embedded introduction further motivates each set of experiments.

Directed Forgetting

Directed forgetting is one method to voluntarily control memory, in which people attempt to forget certain information and to remember other information (see MacLeod, 1998, for a review). In a typical directed forgetting experiment, participants initially encode everything they encounter and are then instructed to forget a particular subset of that information (e.g., Basden, Basden, & Gargano, 1993; Bjork, 1989). After this process, participants complete a surprise memory test in which they try to remember everything they studied previously regardless of whether they were originally told to forget it. Using this directed forgetting paradigm researchers have consistently found a phenomenon termed the *directed forgetting effect*, in which people exhibit better memory for items that they were originally instructed to remember compared to items that they were originally instructed to forget. This directed forgetting effect holds even when participants are incentivized to recall to-be-forgotten items (MacLeod, 1999), highlighting that the effect is not due to demand characteristics. Results from these experiments thus demonstrate that people are capable of voluntarily controlling the contents of their memory following directed forgetting instructions.

Additional Forms of Motivated Forgetting

Directed forgetting is not the only method to control memory. Additional examples of motivated forgetting include retrieval suppression (e.g., Anderson & Huddleston, 2012) and extinction of conditioned fear responses (e.g., Schiller, Monfils, Raio, Johnson, LeDoux, & Phelps, 2010). Retrieval suppression has been studied extensively by Michael Anderson using the Think/No-Think paradigm (e.g., Anderson & Green, 2001; Anderson et al., 2004). In this experimental protocol, participants first learn

a set of paired-associates up to a criterion level. Then, in the critical retrieval suppression phase, participants attempt to retrieve (i.e., the Think condition) or to avoid retrieving (i.e., the No-Think condition) previously learned associates in response to cue words. After performing this type of memory control, participants complete a final memory test with independent cue words. Anderson and colleagues find that people retrieve significantly fewer words from the No-Think condition compared to baseline words that were studied but not included in the Think/No-Think phase. Importantly, these findings indicate that suppressing the retrieval of previously learned memories made them more difficult to retrieve at a future test. This paradigm, therefore, exemplifies that attempting to suppress the retrieval of previously learned memories can help people forget these memories.

Another example of motivated forgetting involves the extinction of conditioned fear responses. Through daily living people can sometimes become conditioned to fear certain entities (i.e., a conditioned fear of dogs), and they may desire to eliminate these unwanted fears. Thus, people may seek professional help via a therapist or may research techniques to extinguish fears on their own, and this initiative demonstrates their desire to perform motivated forgetting. Schiller et al. (2010) demonstrated that they could facilitate the extinction of conditioned fear by taking advantage of the reconsolidation phase of memory. In particular, they found better extinction of fear responses in humans when participants partook in the extinction phase (i.e., repeated re-exposure to the conditioned feared stimulus without the presentation of the unconditioned stimulus) within a 4-hour window after reactivating the conditioned fear memory. Thus, forgetting of a conditioned

fear response benefited from recently reactivating the memory shortly before conducting extinction re-exposure.

These examples illustrate the range of methods available to implement memory control. Some methods are better suited for some situations than others, and presumably they each operate by somewhat different mechanisms. For instance, whereas retrieval suppression is thought to rely on inhibition of previously-learned memories (e.g., see Anderson & Huddleston, 2012), directed forgetting need not necessarily rely on a similar suppression mechanism. Moreover, directed forgetting within working memory involves controlling memory representations that are currently held in mind, as opposed to supra-span sets of memoranda included in typical long-term directed forgetting paradigms. Correspondingly, the manner in which each type of forgetting is executed likely relies on different control processes. Fortunately, this variety equips people with an entire arsenal of possible techniques that they can use to control their memory, allowing them to implement different techniques depending on which is most applicable to their current situation.

Current Project

Most directed forgetting research has focused on the context of long-term memory, using experiments with lengthy stimulus lists and long delays between the initial encoding period and the memory test (e.g., Geiselman, Bjork, & Fishman, 1983; MacLeod, 1975; Sahakyan & Kelley, 2002; Sheard & MacLeod, 2005). My dissertation steps outside this standard paradigm, examining directed forgetting within the context of working memory (see also Nee, Jonides, & Berman, 2007; Nee & Jonides, 2008, 2009; Oberauer, 2001; Zhang, Leung, & Johnson, 2003). Working memory involves the short-

term storage and manipulation of information that is actively held in mind. Typically, short lists of up to seven items are used and memory is tested after a delay of several seconds (e.g., Jonides et al., 2008). My dissertation aims to understand how people control working memory representations via directed forgetting and to examine the outcomes of this type of motivated forgetting.

In a series of experiments, I test several consequences and mechanisms of performing directed forgetting in working memory. Implementing directed forgetting within working memory may even permit more efficient forgetting, as the targeted memoranda are in a relatively active state, the memoranda have yet to be extensively committed to long-term memory, and there are fewer items over which to exert this type of cognitive control. Building on this possibility, my dissertation addresses two primary research aims: (1) How effectively can directed forgetting be implemented in working memory? and (2) What is the role of sub-vocal rehearsal in this type of directed forgetting?

I investigate these broad research questions with seven experiments that are reported in three chapters (see Table 1.1 for a summary). Chapters 2 and 3 include experiments that probe the effectiveness of this form of directed forgetting by testing the relative susceptibility of to-be-remembered and to-be-forgotten items to various forms of memorial interference. Specifically, Chapter 2 reports the influence of directed forgetting on semantic interference and false memories, and Chapter 3 assesses the effect of directed forgetting on proactive interference. Moreover, both chapters include experiments that assess the long-term effectiveness of controlling the contents of working memory. Next, Chapter 4 includes three experiments that investigate the role of rehearsal

in directed forgetting. One experiment tests the influence of articulatory suppression on this type of directed forgetting to determine if disruption of sub-vocal rehearsal with this secondary task helps or hinders forgetting. Another experiment examines whether directed forgetting in working memory can be performed in the absence of simultaneously encoded competitors to remember. And, finally, a third experiment combines these experimental manipulations to investigate whether articulatory suppression exerts similar effects when to-be-remembered competitors are not present.

Table 1.1 *Outline of the experiments on directed forgetting (DF) in working memory (WM) included in this dissertation. Several experiments involve surprise long-term memory (LTM) tests and some experiments introduce an articulatory suppression (AS) manipulation.*

Aim	Chapter	Experiment
	Chapter 1: Introduction	
Aim 1: Effectiveness of DF in WM		
	Chapter 2: Effect of DF on Semantic Effects	
		Exp 1: DF & Semantic Effects in WM
		Exp 2: DF & Semantic Effects in WM & LTM
	Chapter 3: Effect of DF on Proactive Interference	
		Exp 1: DF & PI (Short inter-stimulus interval)
		Exp 2: DF & PI (Long inter-stimulus interval)
Aim 2: Role of Rehearsal in DF within WM		
	Chapter 4: Effect of AS & Competitors Manipulations on DF in WM	
		Exp 1: Effect of AS on DF in WM
		Exp 2: Competitors
		Exp 3: AS & Competitors
	Chapter 5: Summary & Future Directions	

This set of seven experiments documents the efficiency of directed forgetting in working memory and begins to address the underlying mechanisms of this form of cognitive control. The experiments included in Chapters 2 and 3 have been previously published in the journals *Memory* (Festini & Reuter-Lorenz, 2013) and *Cognitive, Affective, and Behavioral Neuroscience* (Festini & Reuter-Lorenz, 2014), respectively. The experiments included in Chapter 4 will soon be submitted to another peer-reviewed

journal. Following discussion of these seven experiments, Chapter 5 presents a brief summary of the findings and considers future directions for additional research on directed forgetting in working memory. Taken together, my dissertation empirically investigates how people perform directed forgetting within working memory, as well as the short- and long-term outcomes of implementing this memory control.

Theoretical Implications

In addition to documenting the repercussions, efficiency, and implementation of this variety of memory control, the experiments in my dissertation also have implications for several broader theoretical frameworks. For instance, the effects of directed forgetting could be interpreted within a levels of processing framework (e.g., Craik & Lockhart, 1972; Craik & Tulving, 1975). Reduced memorial effects for to-be-forgotten items could be the result of weaker processing. Thus, designating something as to-be-forgotten could promote shallow processing, whereas designating something as to-be-remembered could promote deep processing. Further, some of the present experiments include tests of long-term memorability following the control of working memory. These experiments thus inform theories of working memory and long-term memory continuity (e.g., see Jonides et al., 2008 for discussion). Finally, although the present research does not include neuroimaging data of its own, the fact that it focuses on control operations in memory implicates prefrontal executive processes (e.g., D'Esposito, Postle, Ballard, & Lease, 1999; Nee et al., 2007; Nee & Jonides, 2009). Moreover, the experiments that test the influence of directed forgetting performed during working memory on the resulting long-term memory of that information are relevant to research that finds a role for the dorsolateral prefrontal cortex in long-term memory formation (e.g., Blumenfeld &

Ranganath, 2006; Ranganath, Cohen, & Brozinsky, 2005) as well as for hippocampally-mediated memorial processes (e.g., Anderson et al., 2004). Discussion relating the present empirical work to these larger theoretical frameworks is included in each subsequent chapter, where appropriate, as well as in the general concluding chapter.

Recap and Overview of Work to be Presented

Directed forgetting in working memory is a method of memory control that operates shortly after encoding. This time frame may allow for particularly proficient memory control, resulting in efficient leveraging of the forget cue. My dissertation tests the memorial repercussions of this form of memory control both in working memory and in long-term memory. Moreover, these experiments also begin to address how people implement this type of directed forgetting. As a whole, my dissertation focuses on directed forgetting within working memory, questioning: How well can people forget? How do they implement this voluntary forgetting?

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Chapter 2: The Short- and Long-Term Consequences of Directed Forgetting in a Working Memory Task

Abstract

Directed forgetting requires the voluntary control of memory. Whereas many studies have examined directed forgetting in long-term memory (LTM), the mechanisms and effects of directed forgetting within working memory (WM) are less well understood. The current study tests how directed forgetting instructions delivered in a WM task influence veridical memory, as well as false memory, over the short and long term. In a modified item-recognition task, Experiment 1 tested WM only and demonstrated that directed forgetting *reduces* false recognition errors and semantic interference. Experiment 2 replicated these WM effects and used a surprise LTM recognition test to assess the long-term effects of directed forgetting in WM. Long-term veridical memory for to-be-remembered lists was better than memory for to-be-forgotten lists—the directed forgetting effect. Moreover, fewer false memories emerged for to-be-forgotten information than for to-be-remembered information in LTM as well. These results indicate that directed forgetting during WM reduces semantic processing of to-be-forgotten lists over the short and long term. Implications for theories of false memory and the mechanisms of directed forgetting within working memory are discussed.

Introduction

Although accurate memory is highly valued, it can also be beneficial to forget certain events. Such strategic control of memory is a topic of considerable current interest, especially given mounting concerns about the enduring and unwanted effects of intrusive traumatic memories (e.g., Banich et al., 2009). The majority of experimental research in this area has focused on voluntary suppression of memoranda by means of directed forgetting manipulations or Think/No-Think instructions within the context of long-term episodic memory tasks (e.g., see Anderson & Green, 2001; Bäuml, Pastötter, & Hanslmayr, 2010; MacLeod, 1975). In contrast, the present chapter investigates the strategic control of memory by examining directed forgetting within a working memory (WM) task. The current goal is to understand how the effort to forget information presented in a WM task affects the fidelity of memory for that information over the short- and long-term. We use the phenomenon of false memory as a lens for examining the extent of meaningful, associative processing of to-be-forgotten information. More specifically, the current studies investigate the short- and long-term consequences of implementing directing forgetting within a WM task, examining true memory, false memory, and semantic interference for to-be-remembered and to-be-forgotten items. The results will help develop and inform theories about the mechanisms of directed forgetting within WM in order to extend our understanding of these control processes beyond their more frequently studied sphere of LTM.

Directed Forgetting in Long-Term Memory

Directed forgetting involves instructing participants to remember certain stimuli and to forget others (see MacLeod, 1998, for a review). In LTM, different methods have

been used to designate to-be-remembered (R) and to-be-forgotten (F) information, and the specific memorial consequences depend heavily on the methodology. In general, however, people tend to exhibit better memory for items they were instructed to remember compared to items they were instructed to forget during a test in which they are asked to try to remember *all* of the presented stimuli regardless of the initial instruction (e.g., Basden, Basden, & Gargano, 1993; MacLeod, 1975). This differential detriment to F items compared to R items is the classic directed forgetting (DF) effect. It persists even when monetary incentives are provided, suggesting that the presence or absence of DF effects is not due to demand characteristics (MacLeod, 1999). Furthermore, a directed forgetting benefit is often observed, in which memory performance is better when only half of the items need to be remembered (i.e., when the other half receive a forget cue) compared to when all of the items need to be remembered.

The two primary methods to distinguish to-be-remembered items versus to-be-forgotten items are the item-method and the list-method. With the *item-method*, instructions to remember or forget are delivered for each item individually, whereas the *list-method* typically requires participants to study an entire list that they are then unexpectedly asked to forget.[1] One critical difference between these two methods is that the list-method allows for thorough encoding of the to-be-forgotten list prior to the forget instruction. With the item-method, participants may attempt to minimize encoding until they know whether the item is one they need to remember. The different mechanisms of

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[1] The list-method can be conducted within-subjects, in which memory for F and R lists is compared within the same individuals, or it can be conducted between-subjects, in which memory for the first list is compared between those who were told to forget and those who were told to remember this list.

forgetting that are thought to underlie these two procedures will be considered later in this report.

Directed Forgetting in Working Memory

Several decades ago there was considerable interest in directed forgetting effects within short-term memory (e.g., Bjork, 1970; Elmes, Adams, & Roediger, 1970; Elmes & Wilkinson, 1971; Homa & Spieker, 1974; Shebilske, Wilder, & Epstein, 1971; Weiner & Reed, 1969; see MacLeod, 1998, for a review). However, the range of set sizes and retention intervals employed in some of these earlier studies varied widely and often far exceeded (e.g., up to 14 pairs of words in Elmes et al., 1970 and up to 24 s or more in Homa & Spieker, 1974) the parameters that characterize short-term or WM according to contemporary models (e.g., Cowan, 2000; Jonides et al., 2008; McElree & Dosher, 1989; Nairne, 2003). Because of these methodological differences, we focus here on the few more recent studies of directed forgetting implemented within a canonical item-recognition paradigm using fewer than seven items and retention intervals not exceeding several seconds (e.g., Nee, Jonides, & Berman, 2007; Nee & Jonides, 2008; Nee & Jonides, 2009; Oberauer, 2001; Zhang, Leung, & Johnson, 2003). None of these more recent studies, however, has examined associative semantic processing effects or the long-term memorial consequences of a WM directed-forgetting manipulation.[2] These are the goals of the current study.

When directed forgetting is implemented within WM, participants view short-lists of stimuli followed by a cue indicating which items to forget. After a short retention

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[2] Note, however, that Elmes et al. (1970) included a variant of a LTM task after STM cuing, and that Marks and Dulaney (2001) examined semantic priming during a secondary lexical decision task during long-term item-based directed forgetting.

interval (i.e., 3 s), a single probe appears, and the participant indicates whether or not that probe is one of the stimuli they are supposed to remember. These directed forgetting instructions in WM, unlike those in LTM, require participants to *reject* F items during the short-term recognition test. Behaviorally, WM studies tend to find that people make more errors and have longer response times (RTs) for F words compared to unstudied control words (Nee et al., 2007). We refer to these lengthened RTs for F words as *directed-forgetting interference*.

Oberauer (2001) parametrically varied the cue-probe interval in a WM directed forgetting task to examine the fate of to-be-forgotten information after different time intervals over which to perform the forgetting. For to-be-remembered items, RTs increased with the set size of the memory load. However, for the to-be-forgotten lists, set size effects were only present at short cue-probe intervals but disappeared within 1 second after the forget cue. In contrast, the RT intrusion effects (i.e., directed-forgetting interference) persisted throughout the longest cue-probe interval of five seconds. Oberauer (2001) interpreted these findings in relation to Cowan's (1988, 1995) WM model: The elimination of the set size effect indicates that to-be-forgotten lists are successfully removed from the focus of attention 1 second after the cue to forget is displayed. However, the persisting directed forgetting interference indicates that these F items have privileged access in LTM over non-presented items.[3]

Together these results suggest that F items remain familiar, making them more difficult for individuals to correctly reject than new probes. However, how deep or

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[3] See also Oberauer (2005) and Lewis-Peacock, Drysdale, Oberauer, & Postle (2011) for more research pertaining to controlling the contents of working memory. Notably, these two papers include modifications of the working memory directed forgetting task, where some items become *temporarily* irrelevant but should not be completely forgotten.

elaborated is this lingering familiarity? Do individuals process and retain the associative

meaning or gist of the to-be-forgotten items from WM? Or, in accord with more

traditional views of short-term memory encoding, do they only retain a mere remnant of

surface-level, perceptual codes of the to-be-forgotten items? Experiment 1 uses the false

working memory phenomenon to address these questions. As explained in the next

section, we use false working memories and semantic interference effects to compare the

associative processing of to-be-forgotten and to-be-remembered items. This approach

enables us to assess the depth of the lingering familiarity of the to-be-forgotten items and

to characterize possible mechanisms of directed forgetting within WM.

False Working Memories

In a recent set of studies, Reuter-Lorenz and colleagues modified the

Deese/Roediger-McDermott (DRM) paradigm (Deese, 1959; Roediger & McDermott,

1995) for use in a canonical WM task. Participants studied a series of four words (e.g.,

"hive," "bumble," "sting", "buzz") that were all semantically related to an unpresented

theme word that could serve as a critical lure (e.g., "bee" in this example). After a 4-

second delay, participants falsely recalled and falsely recognized critical lures more often

than new words, whether or not the delay was filled with a distracting task (Atkins &

Reuter-Lorenz, 2008, 2011; Flegal, Atkins & Reuter-Lorenz, 2010; see also Coane,

McBride, Raulerson, & Jordan, 2007). In the recognition version, correct rejections of

critical lures took significantly longer than correct rejections of new, unrelated words.

This difference in RT reflects a semantic interference effect (SIE). Flegal et al. (2010)

have demonstrated that the frequency and phenomenology of false working memories are

virtually indistinguishable from false long-term memories, suggesting that similar or common processes underlie both forms of memory distortion.

In the current study, we test how the instruction to forget one of two associatively related lists presented in a WM item-recognition task influences false recognition and semantic interference effects for critical associates of the to-be-forgotten list. We compare the frequency of false recognition errors and the magnitude of semantic interference for critical lures associated with the to-be-remembered versus the to-be-forgotten lists. This approach enables us to assess whether the strategic attempt to control the contents of WM extends to the associates of the to-be-forgotten memoranda, thus revealing the extent of the forgetting and furthering the characterization of directed forgetting within WM.

Although the effects of directed forgetting on false memories have previously been studied in LTM, the results have varied depending in part on the directed forgetting method employed. One list-method experiment found *increased* false memories for critical lures associated with F lists (Kimball & Bjork, 2002), whereas another experiment found *similar* levels of false memories for critical lures associated with F and R lists (Seamon, Luo, Shulman, Toner, & Caglar, 2002). In contrast, an item-method experiment found evidence for *reduced* false memories for critical lures associated with F items (Marche, Brainerd, Lane, & Loehr, 2005; see also Lee, 2008).

In our WM version of the directed forgetting task, two 3-item lists are presented during the encoding interval, which is followed by a forget cue that specifies the list that should be forgotten. Superficially, this procedure resembles the list-method because a single forget cue refers at once to an entire list. However, the lists are short and appear

only briefly before the forget cue arrives, so, participants may encode both lists minimally until they know which one to commit to memory. In this respect, the encoding strategy evoked by our procedure may be more similar to the item-method. If this reasoning is correct, then we expect that directed forgetting will reduce false working memories, as in the LTM study by Marche et al. (2005). Furthermore, the time it takes to reject associated lures (Atkins & Reuter-Lorenz, 2008) provides an additional sensitive index of semantic processing which we also expect to reveal reduced interference for to-be-forgotten lists.

<div align="center">

Experiment 1

</div>

Method

  Participants. Thirty-five individuals (28 women) volunteered to participate in this study.[4] Participants ($M = 20.31$ years) received \$10/hour or course credit as compensation, and all participants were treated within the ethical guidelines of the American Psychological Association.

  Materials. Stimuli were selected from lists developed in our laboratory to examine false working memories (e.g., Atkins & Reuter-Lorenz, 2008; Flegal et al., 2010) based on previously published DRM lists (Roediger, Watson, McDermott, & Gallo, 2001) and the University of South Florida Free Association Norms (Nelson, McEvoy, & Schreiber, 1998). For this experiment, 112 3-item associatively related lists were used.

  Procedure. This experiment implemented a WM variant of the classic DRM paradigm (Atkins & Reuter-Lorenz, 2008; Atkins & Reuter-Lorenz, 2011) in which a

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[4] Three additional participants were excluded due to poor task performance or because they were non-native English speakers.

directed forgetting cue was also presented (see Figure 2.1 for a task diagram). On each

trial, two lists of three semantically related words were presented, one list on either side

of a fixation cross. Participants studied these six words for 3 s. After the study phase and

an inter-stimulus interval (ISI) of 250 ms, a forget cue appeared, positioned randomly to

the left or right of fixation, for 2 s, indicating which list the participant was supposed to

forget. After a 3-second unfilled retention interval, a single recognition probe word

appeared in the center of the screen. The participant then indicated via a mouse button

press whether or not that probe was included in the set of to-be-remembered words.

Participants were instructed to make this response as quickly and accurately as possible.

An inter-trial interval (ITI) of 1500 ms preceded the next set of six words.
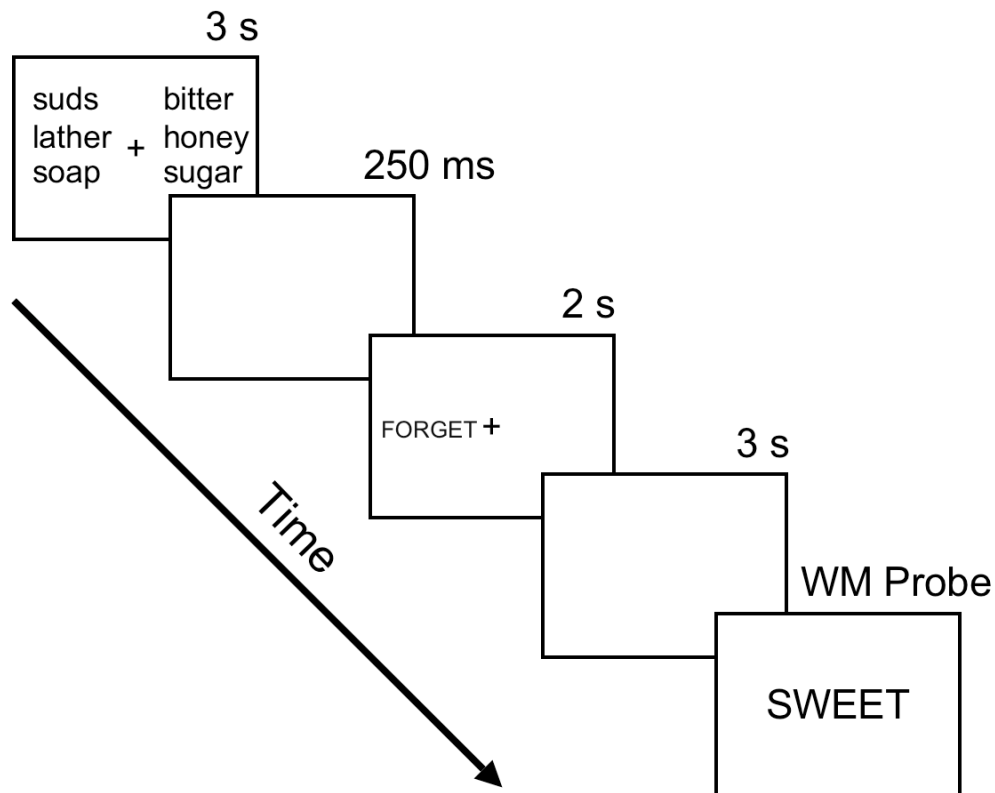
Figure 2.1 *Diagram of the false memory directed forgetting task as implemented in Experiment 1. In this example, the probe word "SWEET" is a Remember-Related probe. In Experiment 2, after the entire working memory phase, participants completed a surprise long-term memory test.*

Each probe word could be one of five different probe-types. Probes included in the set of to-be-remembered words are positive probes that require a "Yes" response and are referred to as "Remember-Studied" probes. Probe words *not* included in the memory set are negative probes because a correct answer requires a "No" response, owing to the fact that the probe either received a forget cue or was not included in the memory set. Unbeknownst to the participants, negative probes could be associatively related to words in the memory set. When the probe word is associatively related to the to-be-remembered words (the R list), it is deemed a "Remember-Related" probe. By the same token, when the probe word is associatively related to the to-be-forgotten words (the F list), it is called a "Forget-Related" probe. When the probe word is *not* related to any of the presented words it is a "New-Unrelated" probe. Finally, when the probe word is included in the F list it is called a "Forget-Studied" probe. Because the number of associatively related lists is limited and to maximize the number of trials in the critical conditions, the probe rate was set at 2/3 negative probes and 1/3 positive probes. One block of 48 trials was administered. There were 8 trials for each negative probe-type and 16 trials for the positive probe-type. Participants completed 12 practice trials before beginning the experimental trials. The relative proportion of probe-types included during the practice trials was identical to that in the experimental trials.

The stimuli were balanced following several guidelines, including consideration of the backward associative strength (BAS), a measure of the associative relatedness (see Hancock & Hicks, 2002; Roediger et al., 2001). The order of the three words was balanced, so that associates with the strongest, middle, and weakest BAS appeared equally often in each of the three positions. Only theme words (i.e., SLEEP) were probed

(e.g., Miller & Wolford, 1999) to ensure that special characteristics of theme words, like a high number of associations, did not contribute to our observed effects. For positive probes, the theme words were included in the studied set of three words, equally often in each of the three positions. Most importantly, each theme word served as a probe equally often for each of the five probe-types (between-subjects). All words were trial unique, such that a particular theme list was never repeated throughout the experiment. Moreover, within-subjects, each probe-type was balanced for BAS so that every probe-type had a similar average BAS. Finally, the two lists of words that were presented simultaneously were balanced for BAS, and the forget cue appeared equally often on either side of the screen. These counterbalanced trials were presented in random order using EPrime 2.0 software (Psychology Software Tools, Inc.).

Results

Positive probe accuracy for to-be-remembered items was high ($M = 0.95$, $SE = 0.01$). The critical analyses focused on false alarm rates and RTs for the four negative probe-types: Forget-Related, Forget-Studied, New-Unrelated, and Remember-Related. See Table 2.1 and Table 2.2 for summary statistics. In the false recognition analyses, false alarms to Remember-Related and Forget-Related probes reflect false memories (i.e., memory intrusions), and false alarms to Forget-Studied probes reflect errors following the directed forgetting instruction. In the RT analyses, semantic interference is reflected in longer RTs to reject Related probes compared to New-Unrelated probes, and directed-forgetting interference is reflected in longer RTs to reject Forget-Studied probes than to

reject New-Unrelated probes. Note that RT means are only derived from correct responses and that these interference scores compare correct rejections.[5]

Table 2.1 *Mean proportion of false alarms (standard error) as a function of probe-type in working memory (WM) in Experiment 1 and WM and long-term memory (LTM) in Experiment 2. Note that Forget-Studied items in the LTM phase of Experiment 2 required a "yes" response, so the false alarm category is not applicable.*

Experiment	Test	Forget-Related	Forget-Studied	New-Unrelated	Remember-Related
1	WM	0.04	0.06	0.03	0.09
		(0.02)	(0.01)	(0.02)	(0.03)
2	WM	0.02	0.04	0.01	0.07
		(0.01)	(0.01)	(0.00)	(0.01)
	LTM	0.24	-	0.13	0.30
		(0.02)		(0.02)	(0.03)

Due to the non-normal distributions associated with false alarm rates, non-parametric tests were used to analyze these data. A Friedman's test confirmed that there were significant differences in the proportion of false alarms among the four negative probe-types, $\chi^2(3) = 16.09$, $p = .001$. Follow-up Wilcoxon Signed Ranks Tests revealed that there were significant false memories for to-be-remembered items, as there were significantly more false alarms to Remember-Related probes than to New-Unrelated probes, $z = 2.87$, $p = .004$, $r = 0.49$. However, there were no significant false memories for probes associated with to-be-forgotten lists; false alarms for Forget-Related and New-

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[5] RT averages were based on a modal count of 8 observations per participant in each probe condition. The average RT for each subject contributed to the overall average.

Unrelated probes did not significantly differ, $z = 0.56$, $p = .577$, $r = 0.10$. Additionally, there were significantly more false alarms to Remember-Related probes than to Forget-Related probes, $z = 2.60$, $p = .009$, $r = 0.44$. Finally, participants were not fully able to follow the forget instruction, as indicated by significantly more false alarms to Forget-Studied probes than to New-Unrelated probes, $z = 2.34$, $p = .019$, $r = 0.40$. To summarize, the false alarm data reveal that there were significant false memories for to-be-remembered items, but not for to-be-forgotten items, and that participants also made significant errors following the forget instruction.

Next, in order to examine semantic interference, we assessed how long it took participants to reject negative probes correctly. A one-way repeated measures analysis of variance (ANOVA) indicated significant differences in RTs among the four negative probe-types, $F(3, 102) = 13.09$, $p < .001$, $\eta_p^2 = 0.278$. Unsurprisingly, correct rejections of New-Unrelated probes were fastest compared to all other probe-types (all $ps \leq .016$, Bonferroni corrected). Significant semantic interference emerged for to-be-remembered lists: Remember-Related probes yielded slower RTs than New-Unrelated probes. Additionally, semantic interference was evident for to-be-forgotten lists: participants took significantly longer to reject Forget-Related probes compared to New-Unrelated probes, suggesting that some remnant of semantic processing was present for to-be-forgotten lists. Even so, participants rejected Forget-Related probes faster than Remember-Related probes, $p = .001$, indicating weaker semantic interference for to-be-forgotten lists. A direct comparison of the SIE for the F and R lists confirmed that the SIE was larger for R lists ($M = 174.83$, $SE = 28.73$) than for F lists ($M = 62.57$, $SE = 19.33$), $t(34) = 4.41$, $p < .001$, $r = 0.60$. Directed-forgetting interference was evident in that RTs to reject Forget-

Studied probes were longer than RTs to reject New-Unrelated probes, *p* = .016. In summary, our RT analyses revealed significant semantic interference for to-be-remembered and to-be-forgotten probes, although the semantic interference was significantly weaker for to-be-forgotten lists. Additionally, the RT analysis indicated directed-forgetting interference, in that participants took longer to reject to-be-forgotten items than new items, as in prior studies using a similar directed forgetting manipulation (e.g., Nee et al., 2007; Oberauer, 2001).

Table 2.2 *Mean response time in milliseconds (standard error) for correct responses as a function of probe-type in working memory (WM) for Experiments 1 and 2. Note that in the WM phase Remember-Studied items required a "yes" response, whereas all other probe-types required a "no" response.*

Experiment	Forget-Related	Forget-Studied	New-Unrelated	Remember-Related	Remember-Studied
1	850.68	891.47	788.11	962.94	826.65
	(33.91)	(43.00)	(30.58)	(42.16)	(31.31)
2	861.97	946.43	824.68	986.44	878.07
	(31.20)	(36.91)	(30.69)	(39.95)	(30.15)

Discussion

Experiment 1 examined the short-term memorial consequences of being instructed to forget a subset of items within WM. The results indicate that directed forgetting reduced false working memory errors and semantic interference associated with the to-be-forgotten list. In particular, participants could reject associates of to-be-forgotten lists more accurately and efficiently than associates of to-be-remembered lists, suggesting that the forget instruction reduced associative processing.

We recognize, however, that we do not know for certain whether participants successfully forgot items in the designated forget list, or whether they simply remembered the sets of items to which they should respond yes or no. In other words, participants may remember both lists equally well, along with a rule dictating the appropriate response to each list, thereby rendering the task one of source discrimination. Countering this possibility, however, is the reduction in false recognition errors and semantic interference from associates of the F lists, which we take to indicate that participants did not maintain the F lists as well as the R lists in WM. If this interpretation is correct, then the to-be-forgotten items should also be less well remembered over the long-term. Furthermore, if the F lists are initially processed less extensively, then we would expect the long-term incidence of false memory errors also to be reduced for F lists because shallow processing has been shown to decrease the incidence of false long-term memories (e.g., Marche et al., 2005; Thapar & McDermott, 2001). These predictions are tested in the next experiment.

Experiment 2 aims to replicate the WM results from Experiment 1, and to further test the memorial consequences of our DF manipulation by including a surprise long-term recognition test at the end of the experimental session. Critically, for the LTM test, participants are asked to recognize (i.e., say "yes" to) *all* studied items regardless of their prior status as to-be-remembered or to-be-forgotten. The WM procedure is the same as in Experiment 1. By also including critical associates of to-be-remembered and to-be-forgotten lists in the long-term recognition test, the experiment further examines the impact of short-term directed forgetting instructions on false long-term memories. If the strategic effort to forget in WM reduces processing of the to-be-forgotten items, as we

suspect, then these items should be less well remembered and lead to fewer false long-term memories than to-be-remembered lists. Note that in the procedure we use, each list is probed only once, either in the WM phase or the LTM phase. Therefore, none of the effects we report can be attributed to prior probing of a specific to-be-remembered or to-be-forgotten list.

<div align="center">Experiment 2</div>

Method

  Participants. Fifty-six individuals (37 women) volunteered to participate in this study.[6] Participants ($M = 18.64$ years) received course credit as compensation, and all participants were treated within the ethical guidelines of the American Psychological Association.

  Materials. Stimuli were identical to those used in Experiment 1. Importantly, the words probed in WM were different from the words probed in LTM. No lists were ever probed twice.

  Procedure. The WM procedure was identical to that used in Experiment 1. After completing the WM trials, participants in Experiment 2 also performed a surprise LTM recognition test. For this test, individuals viewed words presented one at a time for a maximum of 4000 ms (termination upon response; ITI = 1750 ms) and were asked to indicate as quickly and accurately as possible whether or not they had studied the word before—no matter if it was previously part of the R or F list. These instructions parallel the standard LTM directed forgetting instructions (e.g., see MacLeod, 1998). The probe rate was consistent with the WM task: 2/3 negative and 1/3 positive probes. An additional

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[6] Two additional participants were excluded due to the failure to respond on many LTM trials or due to previously completing two other memory experiments on the same day.

16 theme words were substituted on studied lists to serve as probes on the latter LTM test. Like the WM probes, the LTM probes could be one of the five probe-types: Forget-Related, Forget-Studied, New-Unrelated, Remember-Related, or Remember-Studied. Notably, however, Forget-Studied probes now required a "yes" response.

The number of trials per probe-type was determined based on several constraints. To maintain the homogeneity of the recognition probes in LTM, only theme words were probed, as was also true in WM. Due to the number of Remember-Studied and Remember-Related probes in the WM recognition test, there was a surplus of F lists that could be probed in LTM. Further, due to our goal to keep the rate of probes that required a "yes" or "no" response equivalent to the rate used in WM, we needed to probe more Related items (which require a "no" response) because in LTM both Forget-Studied and Remember-Studied probes require a "yes" response. As a result, in the LTM recognition test there were 8 trials per probe-type, except for the inclusion of 16 Forget-Related probes, for a total of 48 trials. A consequence of this design feature is that there were more opportunities for false alarms to F lists than to R lists in the LTM recognition test, which could complicate the comparison of false memories of F lists and R lists in LTM. We address this by only examining the proportion of false alarms between F and R lists, as a proportion takes the unequal number of trials into consideration. Further, supplementary analysis of only the first 8 trials of Forget-Related probes in LTM produced equivalent results.

Results

Working Memory. Accuracy of to-be-remembered positive probes was high ($M = 0.94$, $SE = 0.01$), as was also true in Experiment 1. A direct comparison of accuracy

and RTs for Remember-Studied probes in Experiments 1 and 2 indicated that participants were similarly fast and accurate in both experiments, $ps > .25$.

Next, statistical analyses were conducted on false alarm rates and RT for the four negative probe-types: Forget-Related, Forget-Studied, New-Unrelated, and Remember-Related.[7] See Table 2.1 and Table 2.2 for summary statistics.

A Friedman's test confirmed that false alarm rates differed significantly among probe-types, $\chi^2(3) = 25.72$, $p < .001$. Consistent with our predictions, New-Unrelated probes were associated with the fewest false alarms, whereas Remember-Related probes were associated with the most. Reliable false memories were present for to-be-remembered lists, as planned follow-up Wilcoxon Signed Ranks Tests indicated that false alarms were more frequent for Remember-Related probes than for New-Unrelated probes, $z = 4.06$, $p < .001$, $r = 0.54$. However, directed forgetting statistically eliminated false memories because false alarms for Forget-Related and New-Unrelated probes did not differ, $z = 1.61$, $p = .107$, $r = 0.22$. Likewise, false recognition was significantly lower for Forget-Related probes than Remember-Related probes, $z = 3.11$, $p = .002$, $r = 0.42$. Finally, our results indicate that participants made errors implementing the forget instruction because false recognition was more frequent for Forget-Studied probes than for New-Unrelated probes, $z = 3.12$, $p = .002$, $r = 0.42$. These results replicated those observed in Experiment 1: in WM there were significant false memories for to-be-remembered lists, reduced false memories for to-be-forgotten lists, and some errors were made implementing the directed forgetting instruction.

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[7] As in Experiment 1, RT averages for the WM phase of Experiment 2 were based on a modal count of 8 observations per participant in each probe condition.

A one-way ANOVA on RTs to negative probes indicated a significant effect of probe-type, $F(3, 165) = 21.98$, $p < .001$, $\eta_p^2 = 0.286$. As expected, New-Unrelated probes were associated with the fastest RTs, which differed reliably from all other conditions, $p < .05$ for all pairwise contrasts. In particular, semantic interference was evident for to-be-remembered lists, as Remember-Related probes were associated with the slowest responses. Similarly, RTs to Forget-Related probes were significantly slower than RTs to New-Unrelated probes, $p = .039$. Nevertheless, participants had significantly slower RTs for Remember-Related probes than Forget-Related probes, $p < .001$, and a direct comparison of the SIE for F and R lists indicated that the SIE was larger for R lists ($M = 161.76$, $SE = 28.76$) than for F lists ($M = 37.29$, $SE = 17.67$), $t(55) = 5.61$, $p < .001$, $r = 0.60$. These RT results replicate those observed in Experiment 1: participants exhibited semantic interference for to-be-remembered and to-be-forgotten lists, but the semantic interference for to-be-forgotten lists was significantly smaller than that for to-be-remembered lists. Additionally, participants exhibited directed-forgetting interference, as it took them longer to reject Forget-Studied probes than New-Unrelated probes.

Long-Term Memory. Similarly, in LTM, statistical analysis focused on false alarm rates for the three negative probe-types: Forget-Related, New-Unrelated, and Remember-Related. Higher error rates in LTM left fewer observations for computing average RT (i.e., the modal observation count was as few as 4 in some conditions), and therefore, we refrain from considering this measure further. Summary statistics for LTM false alarms are also included in Table 2.1.

First, we assessed participants' memory accuracy for studied items. The standard DF effect was evident in LTM ($M = 0.19$, $SE = 0.03$): accuracy for Remember-Studied

probes ($M = 0.56$, $SE = 0.03$) was reliably greater than for Forget-Studied probes ($M = 0.36$, $SE = 0.03$), $t(55) = 5.90$, $p < .001$, $r = 0.62$. We also calculated A′ and B″, which are nonparametric indices of sensitivity and response bias, respectively (see Snodgrass & Corwin, 1988; Snodgrass, Levy-Berger, & Haydon, 1985). For instance, A′ is similar to the d′ measure of sensitivity, but it allows calculation of sensitivity if individuals have false alarm rates of 0 and/or hit rates of 1. A′ and B″ were calculated using the Remember-Studied hit rate and the total false alarm rate and by using the Forget-Studied hit rate and the total false alarm rate separately for each subject. The average A′ for to-be-remembered items was 0.74, and the average A′ for to-be-forgotten items was 0.62. Both of these values indicate that performance was above chance—an A′ of 0.50 connotes chance performance. Further, a paired-samples t-test comparing these measures of A′ revealed that participants had worse discriminability for to-be-forgotten items than for to-be-remembered items, $t(55) = 4.42$, $p < .001$, $r = 0.51$, which is consistent with the directed forgetting effect. Additionally, participants displayed similar levels of response bias for Forget-Studied items (B″ = 0.22) and Remember-Studied items (B″ = 0.19), $t(55) = 0.80$, $p = .427$, $r = 0.11$.

Next, we assessed false memories for associates of the studied lists. A Friedman's test indicated that false alarm rates differed significantly among the probe-types, $\chi^2(2) = 32.86$, $p < .001$. In LTM, false memories were present for both to-be-remembered and to-be-forgotten lists: New-Unrelated probes were associated with the fewest false alarms, and this rate was significantly lower than the proportion of false alarms for Remember-Related probes and Forget-Related probes, $ps < .001$ for both follow-up Wilcoxon Signed Ranks Tests. Nevertheless, there were significantly more false memories for to-be-

remembered lists than for to-be-forgotten lists, as the proportion of false alarms for Remember-Related probes was significantly greater than those for Forget-Related probes, $z = 2.46$, $p = .014$, $r = 0.33$.

Discussion

Experiment 2 replicated the WM effects observed in Experiment 1. Within the WM phase, directed forgetting virtually eliminated semantic errors, in that the false alarm rates for Forget-Related and New-Unrelated probes did not differ reliably, and false recognition for Forget-Related words was significantly reduced compared to Remember-Related words. Likewise, RT measures revealed greater semantic interference for probes associated with to-be-remembered lists than for associates of the to-be-forgotten lists. Nevertheless, participants still took significantly longer to reject a Forget-Related probe than a New-Unrelated probe indicating some persisting semantic interference. Thus, directed forgetting reduced but did not completely eliminate semantic effects in WM.

Importantly, Experiment 2 documented the long-term memorial consequences of directed forgetting instructions given during a WM task. First, the LTM results revealed that people have better memory for Remember-Studied probes than Forget-Studied probes—the classic DF effect. This indicates that even though performing the WM task need not depend on actually forgetting the designated items, better memory over the long term suggests that people are preferentially processing the to-be-remembered list. Likewise, they show more false recognition for Remember-Related probes than Forget-Related probes, providing evidence that semantic processing is greater for R lists. Nevertheless, false recognition for Forget-Related probes was greater than for New-

Unrelated probes, indicating that directed forgetting during WM reduced but did not eliminate false long-term memories.

General Discussion

The present results indicate that directed forgetting in working memory reduces semantic processing and the long-term memorability of to-be-forgotten items. Evidence for diminished semantic processing is threefold. First, participants showed reduced false recognition in the WM task for associates of to-be-forgotten lists compared to associates of to-be-remembered lists. In fact, false recognition errors did not significantly differ between associates of to-be-forgotten lists and new, unstudied words. Second, consistent with the false recognition results, participants showed reduced semantic interference for to-be-forgotten items in the WM task. The RTs to reject related probes compared to new probes were larger for to-be-remembered items than for to-be-forgotten items. Third, false recognition in LTM was similarly reduced for associates of to-be-forgotten lists compared to associates of to-be-remembered lists. Thus, the directed forgetting instruction delivered during WM reduced semantic processing across both short and long delays. Finally, directed forgetting in WM reduced long-term veridical memory for words on the forget list, and produced the canonical directed forgetting effect, whereby even when asked to remember *all* items that were previously studied, words on to-be-remembered lists were better recognized than words on to-be-forgotten lists.

The inclusion of a LTM test also permitted comparisons of our results to the prior directed forgetting studies that examined false long-term memories. The reduced false recognition of to-be-forgotten lists compared with to-be-remembered lists was similar to the results of Marche et al. (2005), who found reduced false recall and reduced false

recognition with item-method directed forgetting. However, our results are different from those of Kimball and Bjork (2002) who found more false recall for F items, as well as those of Seamon et al. (2002) who found similar levels of false recall for F items. Both of these latter studies used list-based directed forgetting for longer lists. Differences in the mechanisms proposed for the list-method and item-method, especially the opportunity to implement selective rehearsal, as we explain below, may contribute to these varying effects of directed forgetting on semantic processing.

Implications for Theories of Directed Forgetting

Most theories of directed forgetting are tied to specific experimental procedures, due primarily to the fact that directed forgetting effects are observed using either recall *or* recognition tests following item-method stimulus presentation, but tend to be observed *only* with recall tests (and not with recognition tests) following list-method presentation (e.g., MacLeod, 1999; but see Sahakyan, Waldum, Benjamin, & Bickett, 2009 for evidence of list-method directed forgetting during recognition tests when recognition is recollection-driven and contextual cues are utilized). This discrepancy has lead to the proposition that item-method and list-method directed forgetting depend on different mechanisms (e.g., Basden et al., 1993; Bjork, 1989).

The effects of item-method stimulus presentation have been attributed to *selective rehearsal*, which refers to the differential rehearsal of to-be-remembered items over to-be-forgotten items (e.g., Bjork, 1972; MacLeod, 1975; Woodward, Park, & Seebohm, 1974) and *set differentiation*, which refers to maintaining segregation between to-be-remembered and to-be-forgotten items (e.g., Bjork, 1972; Horton & Petruk, 1980). The most prominent mechanisms proposed for list-method effects are *retrieval inhibition*,

whereby to-be-forgotten items are selectively inhibited during recall tests (e.g.,

Geiselman & Bagheri, 1985; Geiselman, Bjork, and Fishman, 1983; MacLeod, 1998)[8],

and the *contextual change account*, whereby an internal context change occurs between

the presentation of the two lists (during the forget cue) that results in better memory for

the to-be-remembered list over the to-be-forgotten list because the context at test better

matches the former encoding context (Sahakyan & Kelley, 2002; cf. Pastötter & Bäuml,

2010). Of particular relevance for the present results is the proposal by Sheard and

MacLeod (2005) that selective rehearsal influences *both* item- and list-method directed

forgetting, based on evidence that unfilled delays before list-method testing magnified the

directed forgetting effect in individuals with high memory capacity. The unfilled delay

allowed more opportunity for selective rehearsal to operate even in this list-method

paradigm.[9]

These theories do not specifically consider directed forgetting within verbal WM,

about which detailed theoretical accounts are currently lacking (although see MacLeod,

1998). We propose, however, that mechanisms theorized to account for directed

forgetting in long-term memory may also operate within a working memory context. As

discussed in the introduction, we believe our WM directed forgetting procedure is more

like the item-method, and the results from the LTM task bear this out. First, as with the

item-method, we observed directed forgetting effects in LTM using recognition testing,

an outcome that would not be expected with the list-method. Second, like the item-

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[8] Note, however, that MacLeod (1989) proposed that the item-method is also influenced by retrieval inhibition, as item-method directed forgetting yielded directed forgetting effects on both explicit and implicit tests of memory.
[9] Sheard & MacLeod (2005) further argue that selective rehearsal is a more parsimonious account, and that the previously observed dissociation between list-method recall and recognition is due to the smaller effect size in list-method directed forgetting.

method, we found better veridical memory, yet more false memories (Marche et al., 2005) for to-be-remembered items in LTM. We interpret this result and the reduction of semantic effects in WM to indicate that participants engage in differential processing of the to-be-remembered lists relative to the to-be-forgotten lists, akin to the selective rehearsal hypothesis. As with item-method directed forgetting where rehearsal can be applied or not on an item-by-item basis, participants in our WM task had the opportunity to selectively rehearse the R list to the exclusion of the F list. Thus, we suggest that the *opportunity for rehearsal* rather than the type of instruction (list- or item-based) may be critical for determining whether selective rehearsal contributes to directed forgetting effects.

According to this selective rehearsal account, to-be-remembered lists receive preferential processing conferred by rehearsal while to-be-forgotten lists do not. Although this mechanism alone could explain the present results, the potential contribution of alternative additional mechanisms should also be considered. For instance, participants could conceivably engage an early perceptual filtering strategy (e.g., see Nee & Jonides, 2009) that immediately selects R lists to the exclusion of F lists. We believe this mechanism is unlikely in the present paradigm, however, because both lists need to be retained until the forget cue appears, which is 250 ms after the offset of the lists. Participants do not know which list to ignore until after their offset, and the initial encoding of both lists must be sufficient to bridge the interval preceding the forget cue.

Another possibility is that directed forgetting also entails an active inhibitory process, whereby the F list is deliberately and effortfully inhibited once the forget cue

appears, suppressing processing of the to-be-forgotten items and their associates. This notion that directed forgetting is an active, resource-demanding inhibitory process is consistent with several previous studies. Behaviorally, forgetting has been shown to interfere with a secondary detection probe task (Fawcett & Taylor, 2008; see also Fawcett & Taylor, 2010; Fawcett & Taylor, 2012; cf. Lee & Lee, 2011). Neurally, forgetting has been linked to a frontal control mechanism (see Nee et al., 2007; Ludowig et al., 2010; Wylie, Foxe, & Taylor, 2008). And, finally, Zacks and Hasher (1994) have proposed the *attentional inhibition hypothesis*, which advocates an active form of inhibition of goal-irrelevant information (see also Hasher & Zacks, 1988). In support of this hypothesis, Zacks, Radvansky, and Hasher (1996) found that compared to younger adults, older adults, who are argued to have deficient inhibition, had more intrusions of F items during an immediate recall test and took longer to reject F probes (compared to new probes) in an immediate recognition task similar to our WM paradigm.

Finally, set differentiation is also likely needed for successful directed forgetting (cf. Bjork, 1972; Horton & Petruk, 1980). Distinguishing between words included on R and F lists is necessary to correctly apply the forget instruction, and this set differentiation may require active control processes as well (i.e., recruitment of frontal networks). Future studies will need to be conducted to determine whether these additional potential mechanisms contribute to directed forgetting within WM to further elucidate *how* people are able to control the contents of memory.

Implications for False Memory Theories

Although the present investigation was not designed to adjudicate between different theories of false memory, the results have some bearing on our understanding of

the mechanisms of memory distortion. Different theories have been proposed to account for false memories, and many share the view that associative activation (e.g., Anderson, 1983; Collins & Loftus, 1975; McClelland & Rumelhart, 1981) of the critical theme word (at encoding, retrieval, or both), along with memory monitoring processes at retrieval, are crucial to explaining these effects (see Gallo, 2006, for a review). In particular, the *activation-monitoring hypothesis* of Roediger, McDermott, and Robinson (1998) builds on Underwood's (1965) original *implicit associative response* hypothesis, which posits that the presentation of related list items automatically activates the associated theme word (see also Johnson, Hashtroudi, & Lindsay, 1993; Roediger et al., 1998). Alternatively, the *fuzzy trace theory* proposes that people make memory decisions based on verbatim traces that correspond to the perceptual properties of the stimulus and gist traces that represent the general meaning of the stimulus (see Reyna & Brainerd, 1995). According to this theory, false memories occur because verbatim traces decay rapidly, inducing people to rely on gist representations to make memory decisions. Finally, *global-matching models* (e.g., Arndt & Hirshman, 1998) propose that false recognition results from the familiarity produced by the summation of memory traces from the associatively related words.

Because we find reduced false memories in WM and LTM with DF, the present results suggest that the implicit associative response *at encoding* cannot be sufficient to produce false memories because presumably such implicit semantic activation should have occurred automatically and equally upon the initial presentation of the to-be-remembered and to-be-forgotten lists. Nevertheless, semantic spreading activation may accompany rehearsal of to-be-remembered items, which could explain the greater

semantic effects for this list compared to the forget list (cf. Goodwin, Meissner, & Ericsson, 2001). Next, consistent with fuzzy trace theory and with the LTM interpretation of Marche et al. (2005), directed forgetting within WM may reduce both verbatim and gist memory traces, thereby reducing both veridical and false memories. More specifically, the reduction in gist memory could contribute to the reduced semantic effects observed for the to-be-forgotten information because strong gist traces would not be present to promote false memory. Finally, the observed results are consistent with global-matching models, in that the forgetting of F items will result in a smaller sum signal of familiarity toward the critical lure, which will contribute to reduced false recognition. Thus, the results of this experiment are in accord with fuzzy trace theory and global-matching models, but can only be explained by the activation-monitoring hypothesis if the extent of the spreading activation varies as a function of the amount of rehearsal that item receives.

Although this experiment showed that directed forgetting decreased semantic effects in both WM and LTM, nonetheless, some associative processing survived the directed forgetting instruction. RT measures of semantic interference remained significant for Forget-Related probes in WM, and Forget-Related probes were more likely to be falsely recognized than New-Unrelated probes in LTM. Directed forgetting thus reduced but did not eliminate false alarms and interference arising from semantic or gist-based processing. Indeed, perhaps sufficient semantic processing persisted to allow for semantic priming of to-be-forgotten items (see Marks & Dulaney, 2001). The lingering semantic representation may have been the result of initial encoding, before the forget cue was presented. Semantic processing also may have continued during the

retention interval after directed forgetting was initiated. In either case, these effects indicate that even within the framework of a WM task, people cannot fully control the content of their memory.

Conclusions

The results from the present pair of experiments demonstrate that directed forgetting instructions provided during WM can reduce semantic effects in both WM and LTM. We observed a decreased incidence of false recognition that was evident within several seconds of the study episode and persisted across a longer delay. Our research, therefore, provides further evidence for the continuity between WM and LTM and the similar semantic and memorial effects observed in both (i.e., Blumenfeld & Ranganath, 2006; Fawcett & Taylor, 2012; Flegal et al., 2010; however see e.g., Rose, Myerson, Roediger, & Hale, 2010). While the precise mechanisms by which people strategically control the contents of WM are not yet known, the present work establishes the utility of our paradigm for investigating this issue and implicates selective rehearsal as a candidate mechanism. In light of the task parameters we used, we believe it is important to consider the *opportunity* for rehearsal as a critical factor, rather than the instruction or stimulus presentation method, which has been emphasized in the past (e.g., Basden et al., 1993; Bjork, 1989). Overall, our research reveals that directed forgetting during working memory reduced the memorability of specific to-be-forgotten items compared to to-be-remembered items in both working memory and long-term memory, and that the semantic associative processing was similarly reduced across both intervals. Thus, the voluntary forgetting of items held in working memory extends to associates of the memoranda contributing to the reduction in semantic effects over short and long delays.

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Chapter 3: Cognitive Control of Familiarity: Directed Forgetting Reduces Proactive Interference in Working Memory

Abstract

Proactive interference (PI) occurs when previously learned information interferes with new learning. In a working memory task, PI induces longer response times and more errors to recent negative probes compared to new probes, presumably because the recent probe's familiarity invites a "yes" response. Warnings, longer inter-trial-intervals, and increased contextual salience of the probes can reduce but not eliminate PI, suggesting that cognitive control over PI is limited. Here we test whether control exerted in the form of intentional forgetting performed during working memory can reduce the magnitude of PI. In two experiments, participants performed a working memory task with directed forgetting instructions and the occasional presentation of recent probes. Surprise long-term memory testing indicated better memory for to-be-remembered than to-be-forgotten items, documenting the classic directed forgetting effect. Critically, in working memory, PI was virtually eliminated for recent probes from prior to-be-forgotten lists compared to recent probes from prior to-be-remembered lists. Thus, cognitive control when executed via directed forgetting can reduce the adverse and otherwise persistent interference from familiarity, an effect that we attribute to attenuated memory representations of to-be-forgotten items.

Introduction

Memory interference permeates our daily lives. For instance, it underlies our tendency to accidentally enter an old password when trying to login to a website, or our inadvertent approach to the parking space where we parked our car yesterday instead of where we parked today. These examples illustrate how proactive interference (PI) from previously learned information interferes with current performance (e.g., Anderson & Neely, 1996; Postman & Underwood, 1973). Because of these adverse interference effects, considerable research effort has aimed to understand their underlying mechanisms and to identify methods that can ameliorate interference in both short- and long-term memory. The aim of the present study is to test whether or not the intentional control of working memory contents through directed forgetting will serve to decrease the amount of PI engendered by the to-be-forgotten information.

Proactive Interference within Working Memory

Although more frequently studied in the long-term domain (for a review see Anderson & Neely, 1996), PI is also clearly evident within working memory (e.g., Carroll, Jalbert, Penney, Neath, Surprenant, & Tehan, 2010; McElree & Dosher, 1989; Monsell, 1978; Nee, Jonides, & Berman, 2007; Nee & Jonides, 2008, 2009; Ralph et al., 2011; Zhang, Leung, & Johnson, 2003). In one canonical working memory task, participants must hold a set of memoranda in mind across a delay period, after which their memory is tested for the current memory set (i.e., with a modified Sternberg item-recognition test; Sternberg, 1966). People generally take longer to correctly reject a probe item that was included in the previous memory set than to correctly reject a new, or relatively non-recent, probe item (e.g., Nee, Jonides & Berman, 2007; Jonides,

Marshuetz, Smith, Reuter-Lorenz, Koeppe, & Hartley, 2000). This lengthened response time to recent probes indicates the influence of PI. Several accounts of potential mechanisms underlying PI have been reported (see Jonides & Nee, 2006), many of which rely on the familiarity of recent probes as the source of the conflict. For instance, according to the biased competition model (Desimone & Duncan, 1995; Kan & Thompson-Schill, 2004), the temporal familiarity of a recent probe biases participants toward an affirmative response when a negative response is truly required. Participants must then overcome this familiarity-induced conflict to achieve the correct response. This process takes time and is not always fully effective, which underlies the lengthened response times and decreased accuracies associated with PI.

Regardless of the mechanism, these interference effects have been shown to be robust, persistent, and pervasive in working memory, as PI remains evident after context, timing, and warning manipulations. Atkins, Berman, Reuter-Lorenz, Lewis, and Jonides (2011) manipulated the contextual salience of memory sets in a recent probes task. For each trial, memoranda were either all fruits or all countries, and these fruit and country trials were intermixed throughout the experimental session. Recent probes could thus originate from memoranda that matched or did not match the semantic context of the current trial. Although contextual mismatching reduced PI, significant levels of PI persisted on these mismatch trials. Additionally, to test the putative decay of working memory representations over time, Berman, Jonides, and Lewis (2009) compared PI after short and long inter-trial-intervals (ITIs). Critically, they found no change in the magnitude of PI with increasing ITI, demonstrating that time alone neither weakened memory representations nor reduced the level of PI.

People are generally unaware of experimental manipulations that induce PI (Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001). Therefore in another study, Berman et al. (2009) specifically instructed participants at the start of the experiment to ignore prior memoranda once a trial had ended in an effort to reduce inadvertent retention of memoranda from one trial to the next. However, these directions had no effect on the magnitude of interference, suggesting that intentional control of PI is limited. Oberauer (2001) also instructed participants to control the contents of their memory, requiring them to render half of the items temporarily irrelevant. Results demonstrated that this intentional memorial control reduced set-size effects in working memory. Nonetheless, participants still exhibited lengthened RTs to temporarily irrelevant words compared to new words, indicating the persistence of intrusion effects (see also Oberauer, 2005). Further, temporal recency of the probes was not varied in this task, leaving the influence of cognitive control on this type of PI open for investigation.

Directed Forgetting within Working Memory

In the present study, we revisit the question: Can the magnitude of PI in a working memory task be reduced by cognitive control? We focus specifically on controlling the contents of memory by means of directed forgetting instructions (for a review see MacLeod, 1998). On each trial of such tasks, participants briefly study two short lists. After the lists disappear, participants are instructed to forget one list and to remember the other one (e.g., Nee & Jonides, 2008, 2009). Thus, control is targeted at a specific subset of items and implemented within seconds of encoding.

Several earlier studies explored the relationship between directed forgetting and PI within short-term memory (Homa & Spieker, 1974; Shebilske, Wilder, & Epstein,

1971; Turvey & Wittlinger, 1969; Weiner & Reed, 1969). However, the parameters of these earlier studies depart from contemporary models of working memory that employ smaller stimulus set sizes and shorter delays before memory tests (e.g., Cowan, 2000; Jonides et al., 2008). For these reasons, we sought to document the effect of directed forgetting on PI using set size and retention interval parameters currently recognized as defining a canonical working memory task (for additional discussion see Festini & Reuter-Lorenz, 2013).

We recently showed that directed forgetting in working memory reduces semantic interference across both short and long delays (Festini & Reuter-Lorenz, 2013). Semantic interference occurs in a working memory task when participants study lists of semantically related words (i.e., "saddle", "gallop", "pony"), and are occasionally probed with a semantically-related lure (i.e., "HORSE," in this example). As documented in prior studies (e.g., Atkins & Reuter-Lorenz, 2008, 2011; Flegal, Atkins, & Reuter-Lorenz, 2010), strong associates of studied words take longer to correctly reject than new, unrelated words, indicating that the semantic association produces interference. Critically, we found that the instruction to forget one of two simultaneously presented lists of associatively-related words reduced the semantic interference (and false memories) for the to-be-forgotten list compared to the to-be-remembered list (Festini & Reuter-Lorenz, 2013).

Our directed forgetting manipulation also reduced long-term memory of to-be-forgotten memoranda. Participants performed a surprise long-term memory test indicating whether or not each probe word was presented at any time during the working memory phase of the experiment, regardless of its prior status as to-be-remembered or to-

be-forgotten. Memory for to-be-forgotten items was significantly reduced compared to memory for to-be-remembered items, indicating that controlling working memory contents also influenced explicit long-term memory for this information. Moreover, fewer false memories for to-be-forgotten items were evident over the long-term, demonstrating that short-term control can reduce long-term semantic distortions. These results indicate that directed forgetting implemented in working memory can effectively control the contents of memory and can reduce semantic interference effects over the short and longer term.

Current Project

For these reasons, in the current project, we aim to determine if cognitive control in the form of directed forgetting can reduce PI within working memory. As reviewed above, PI is relatively immune to longer delays between trials, salient changes in trial context, and warning instructions (Atkins et al., 2011; Berman et al., 2009). It is worth noting that recency-induced PI is not evident in semantic or perceptual judgment tasks, which lack working memory requirements and render the temporal familiarity of a probe item irrelevant (Craig, Berman, Jonides, & Lustig, 2013). Nevertheless, the present study is concerned with working memory performance, making temporal recency a task relevant dimension.

Our prior evidence for reduced memorability, reduced semantic interference, and reduced gist-based distortions suggests that directed forgetting can attenuate the memorial representations of to-be-forgotten items. Decreasing an item's memory strength may also reduce its familiarity, resulting in reduced PI for to-be-forgotten information.

Experiment 1 will test this hypothesis and will determine if controlling the contents of working memory via directed forgetting can eliminate the persistent effects of PI.

Experiment 1

Method

Participants. Thirty individuals (24 women) volunteered to participate in this study. This sample size was selected to ensure sufficient power. Prior studies that used a recent probes manipulation to examine proactive interference had sample sizes of 18 (Atkins et al., 2011) and 25 (Nee et al., 2007), for example. Two additional subjects were excluded from our sample due to poor working memory performance that fell below 2 standard deviations of the mean. Participants ($M = 18.97$ years, $SE = 0.19$) received course credit as compensation, and all participants were treated within the ethical guidelines of the American Psychological Association.

Materials. Words were selected from the MRC database (http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm). Words were selected according to the following criteria: length of 3 to 8 letters, 1 to 3 syllables, Kucera & Francis written frequency of 10-150, familiarity of 400-650, and concreteness rating of 300-600. A unique memory set was presented on every trial, yielding a total of 288 to-be-encoded words. Additional words with the same characteristics were used as new probes.

Procedure. This experiment implemented a working memory task with directed forgetting instructions (e.g., Festini & Reuter-Lorenz, 2013; Nee, Jonides, & Berman, 2007) and a recent probes manipulation (e.g., Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998; Monsell, 1978). See Figure 3.1 for a task diagram. On each trial, two sets of three words were presented, one list on either side of a fixation cross.

Participants studied these six words for 3 seconds. After the study phase and an inter-stimulus interval (ISI) of 250 milliseconds, a forget cue appeared, positioned randomly to the left or right of fixation for 2 seconds, indicating which list the participant was supposed to forget. After a 3-second unfilled retention interval, a single recognition probe word appeared in the center of the screen. The participant then indicated via a mouse button press whether or not that probe was included in the current set of to-be-remembered words. Participants were instructed to make this response as quickly and accurately as possible. An inter-trial interval (ITI) of 1500 milliseconds preceded the next set of six words. These trials were pseudorandomized and were presented using EPrime 2.0 software (Psychology Software Tools, Inc.).
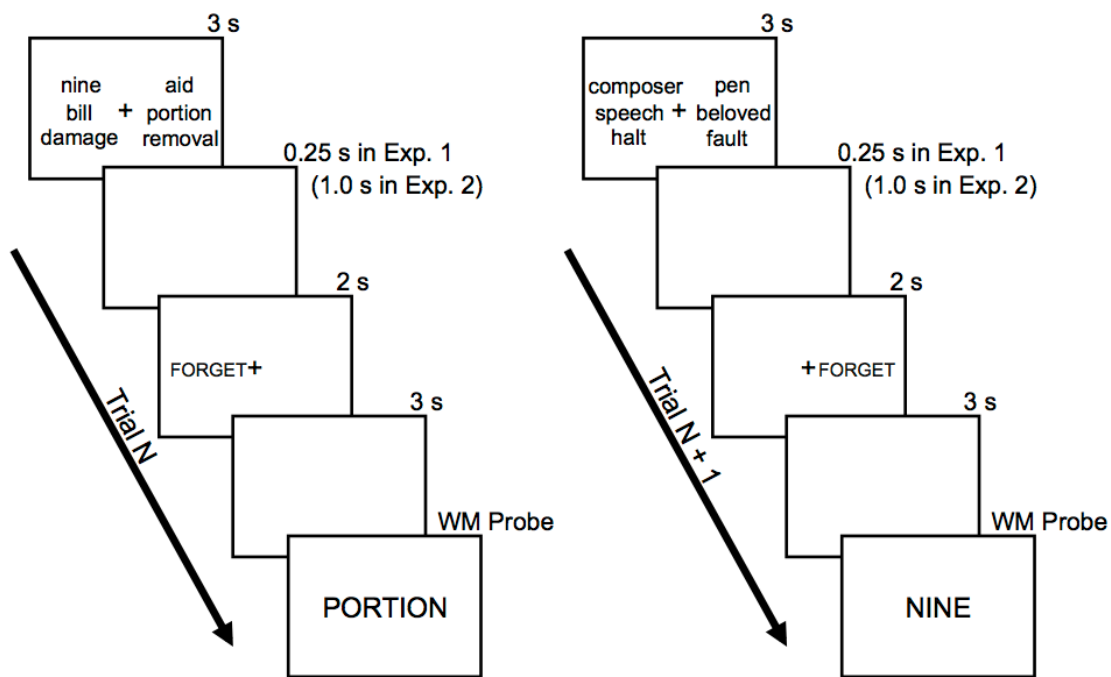
Figure 3.1 *Diagram of the recent probe/directed forgetting task. In this example, the probe word "PORTION" is a Remember-Studied probe because it was included as a to-be-remembered word on the current trial. The probe word "NINE" is a Forget-Recent probe because it was a to-be-forgotten word on the previous trial. After participants completed the entire working memory (WM) phase, participants completed a surprise long-term memory recognition test.*

Remember probes occurred on half of the trials, in which the probe word was one of the words participants were supposed to remember. Negative probes, which did not appear in the current memory set, were presented in the remaining half of the trials. Unbeknownst to the participants, two-thirds of these negative probes were words that had been presented on the *previous* trial.[10] These recent probes could have originated from either the prior to-be-remembered or the prior to-be-forgotten subset, and are designated here as Remember-Recent and Forget-Recent probes, respectively. The remaining third of the negative probes were New probe words that had not been previously studied. The working memory block consisted of 48 trials, and the response rate was set at 50% "yes" trials and 50% "no" trials. This design yielded 24 Remember trials and 8 trials for each of the negative probe-types (Remember-Recent, Forget-Recent, or New). Participants completed 12 practice trials before beginning the experimental trials. The relative proportion of probe-types included during the practice was identical to that in the experimental trials.

The probe words were balanced following several guidelines. Importantly, each recent probe appeared equally often as a Remember-Recent probe and as a Forget-Recent probe, between-subjects. Further, the probe words came equally often from the right or left side of the screen and were balanced to come from each of the three list positions. The right and left side of the screen also received a forget cue on an equal number of trials, and the same side of the screen never received a forget cue more than three times in a row.

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[10] Examination of exit surveys confirmed that participants were unaware of the recent probe manipulation, as participants did not describe certain trials as being more difficult than others when questioned.

After the entire working memory phase, participants also completed a surprise long-term recognition memory test, in which they were asked to try to remember any of the words they had previously seen, no matter if they originally were instructed to remember or to forget them. For the long-term memory test, a single probe word was displayed in the center of the screen for a maximum of 4 seconds (termination upon response), with an ISI of 1500 ms. Again, participants were instructed to make this response as quickly and as accurately as possible. Notably, none of the long-term memory probe words had previously been probed within working memory and were therefore viewed only once previously as either a to-be-remembered or a to-be-forgotten word. There were 48 trials in the long-term recognition test composed of 24 "no" trials, consisting of new words that had not been previously studied, and 24 "yes" trials, consisting of 12 previously to-be-remembered words and 12 previously to-be-forgotten words. The length of the long-term memory test was selected to match the number of working memory trials and because prior experiments (e.g., Festini & Reuter-Lorenz, 2013) demonstrated that tests of this length were sensitive to directed forgetting effects. There were two sets of possible long-term memory probes, counterbalanced between subjects. Identical New probes were used in each set. The Remember and Forget long-term memory probes were balanced such that each was originally presented on a working memory trial that had previously received a New, Remember Recent, or Forget Recent probe equally often. Finally, each probe originated equally often in each of the three list positions.

Critically, in long-term memory participants should now indicate that they studied both the to-be-remembered and to-be-forgotten words. This long-term memory test

allowed us to confirm, based on long-term memory accuracy, whether or not participants

performed directed forgetting within working memory. Successful implementation of

directed forgetting would be reflected in inferior long-term memory for to-be-forgotten

items than for to-be-remembered items. If a long-term memory directed forgetting effect

is observed, this eliminates the possibility that participants were remembering both sets

of words along with a tag to indicate whether or not they were supposed to remember that

item.

Results

   Working Memory. Working memory performance was highly accurate for both

positive probes ($M = 0.91$, $SE = 0.01$) and negative probes ($M = 0.97$, $SE = 0.01$),

however, a Wilcoxon Signed Ranks test indicated that participants were more accurate

for negative probes than for positive probes, $z = 3.76$, $p < .001$. Further, although

accuracy was lowest for Remember-Recent probes, a Friedman's test revealed no

significant differences among New probes, Forget-Recent probes, or Remember-Recent

probes, $\chi^2(2) = 3.20$, $p = .202$. See Table 3.1 for descriptive statistics. Non-parametric

Wilcoxon Signed Ranks tests and Friedman's tests were used due to the non-normal

distributions of accuracy.

Table 3.1 *Mean accuracy and mean response time (RT) in Experiment 1 as a function of probe-type in working memory. Mean RTs are reported in milliseconds. Only correct responses are included in the RT average. Note that in the working memory phase Remember-Studied items required a "yes" response, whereas all other probe-types required a "no" response. Standard error is reported in parentheses.*

	Forget-Recent	New	Remember-Recent	Remember-Studied
Accuracy	0.98 (0.01)	0.98 (0.01)	0.94 (0.02)	0.91 (0.01)
RT	848.28 (32.13)	830.58 (42.62)	911.94 (41.52)	831.70 (37.58)
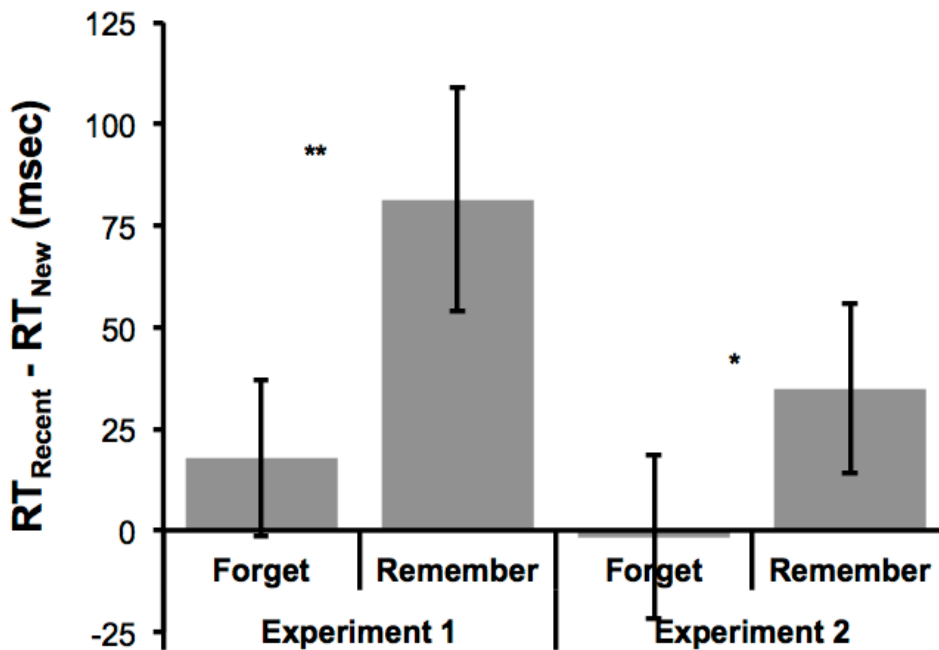
Figure 3.2 *Average magnitude of proactive interference in working memory for to-be-forgotten items and to-be-remembered items (± standard error) in Experiment 1 and Experiment 2. Proactive interference was calculated by subtracting the average response time to correctly reject a New probe from the average response time to correctly reject a Recent probe. Proactive interference was significantly reduced for to-be-forgotten items compared to to-be-remembered items in Experiment 1 (p < .01) and in Experiment 2 (p < .05).*

A repeated-measures Analysis of Variance (ANOVA) on average correct RTs to negative probes revealed significant differences as a function of probe-type, $F(2, 58) = 7.17$, $p < .002$, $\eta_p^2 = 0.198$. Follow-up, Bonferroni-corrected, pairwise comparisons revealed that RTs were longer for Remember-Recent probes than for New probes ($p = .018$), which reflects PI for to-be-remembered information. Further, RTs to reject Remember-Recent probes were also significantly longer than RTs to reject Forget-Recent probes ($p = .011$). Notably, RTs for Forget-Recent and New probes did not reliably differ ($p = 1$). This indicates that PI was virtually eliminated for to-be-forgotten items within

working memory. Descriptive statistics of RTs are also reported in Table 3.1. For illustrative purposes, Figure 3.2 depicts the level of PI in the Forget and Remember conditions, calculated by simply subtracting the average RT to correctly reject a new probe from the average RT to correctly reject each recent probe-type.

Long-term Memory. The surprise long-term memory recognition test allowed us to determine the long-term effectiveness of directed forgetting implemented in working memory. In the long-term memory test, participants were asked to indicate whether or not they studied the word before, no matter if it was previously to-be-remembered or to-be-forgotten. Assessment of long-term memory accuracy revealed the classic directed forgetting effect: Participants had better memory for to-be-remembered items ($M = 0.57$, $SE = 0.03$) than for to-be-forgotten items ($M = 0.29$, $SE = 0.03$), $t(29) = 7.09$, $p < .001$, $r = 0.80$[11]. Accuracy for New probes in long-term memory was also fairly high ($M = 0.77$, $SE = 0.02$), connoting careful performance on this surprise long-term memory test. This false alarm rate of 23% for New probes is reasonable given the difficulty of a long-term memory test after incidental encoding. It parallels the false alarm rate of similar memory tests (e.g., Stark & Okado, 2003).

We also computed nonparametric indices of sensitivity and response bias: A′ and B″ respectively (see Snodgrass & Corwin, 1988; Stanislaw & Todorov, 1999). A paired-samples t-test indicated that participants had worse discriminability for to-be-forgotten items ($M = 0.54$, $SE = 0.03$) than for to-be-remembered items ($M = 0.75$, $SE = 0.02$), $t(29) = 6.41$, $p < .001$, $r = 0.77$, which is consistent with the directed forgetting effect. Further, there was no difference in response bias for to-be-remembered ($M = 0.16$, $SE =$

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[11] The statistic "r" is a measure of effect size, calculated as indicated by Rosenthal (1991).

0.06) and to-be-forgotten items ($M = 0.19$, $SE = 0.04$), $t(29) = 0.52$, $p = .610$, $r = 0.10$.

These results confirm that directed forgetting in working memory was successfully implemented, and that it leads to deficient long-term memory for the to-be-forgotten items.

Discussion

Experiment 1 examined whether performing directed forgetting within working memory would decrease the magnitude of PI for to-be-forgotten items. Results demonstrated that participants were able to correctly reject recent to-be-forgotten items significantly faster than they were able to correctly reject recent to-be-remembered items, which is indicative of greater PI for to-be-remembered items. In fact, participants rejected recent to-be-forgotten items as easily as they rejected new items. Thus, these results indicate that instructing people to forget a subset of items in working memory successfully reduced proactive interference for these to-be-forgotten items.

We interpret these results to indicate that people are able to control the contents of working memory by actively forgetting targeted information. An alternate explanation is that PI was reduced because the to-be-forgotten items were not encoded into working memory initially. That is, the short 250 ms ISI between list offset and forget cue onset may have allowed participants to rely on iconic memory representations of both lists and to postpone encoding of the three to-be-remembered items until the forget cue appeared. To rule out this potential alternative, in Experiment 2 we lengthened the ISI between the offset of the six words and the onset of the forget cue to 1000 ms, an ISI beyond the limit of iconic memory (Coltheart, 1980; Lu, Neuse, Madigan, & Dosher, 2005) and identical to that used in other investigations of directed forgetting in working memory (e.g., Smith,

Eich, Cebenoyan, & Malapani, 2011; Nee & Jonides, 2008). If we can replicate the reduced PI effect for to-be-forgotten items found in Experiment 1 using these new parameters, the results would rule against a delayed encoding strategy, and would favor an interpretation of cognitive control in response to the directed forgetting instruction.

Experiment 2

Method

Participants. A new group of thirty individuals (20 women) volunteered to participate in this study. This sample size was selected to match that of Experiment 1. Nine additional subjects were excluded due to poor working memory performance that fell below 2 standard deviations of the mean, due to average RTs longer than 2.5 standard deviations of the mean, or due to the failure to follow task instructions. Participants (M = 19.93 years, SE = 0.35) received \$10 as compensation, and all participants were treated within the ethical guidelines of the American Psychological Association.

Materials. The materials were identical to those used in Experiment 1.

Procedure. This Experiment was identical to that in Experiment 1, with one key difference. In Experiment 2, the ISI between the offset of the six words and the presentation of the forget cue was lengthened to 1 second.

Results

Working Memory. Working memory performance was highly accurate for both positive probes (M = 0.88, SE = 0.02) and negative probes (M = 0.97, SE = 0.01), and a Wilcoxon Signed Ranks test indicated that participants were more accurate for negative probes than for positive probes, z = 3.87, p < .001. A Friedman's test comparing accuracy among negative probes revealed a significant difference, $\chi^2(2)$ = 10.86, p = .004. Follow-

up Wilcoxon Signed Ranks tests revealed that participants made more errors for Remember-Recent probes than for New probes, $z = 2.91$, $p = .004$, and made more errors for Remember-Recent probes than for Forget-Recent probes, $z = 1.98$, $p = .048$. There was no significant difference in accuracy for Forget-Recent and New probes, $z = 1.63$, $p = .102$. See Table 3.2 for descriptive statistics. Thus, these results indicate that directed forgetting reduced the false alarm rate for Forget-Recent probes within working memory to a level similar to that for New probes. Further, participants made more false alarms to recent to-be-remembered probes than to recent to-be-forgotten probes. Both effects are consistent with a reduction in PI for to-be-forgotten items.

Table 3.2 *Mean accuracy and mean response time (RT) in Experiment 2 as a function of probe-type in working memory. Mean RTs are reported in milliseconds. Only correct responses are included in the RT average. Note that in the working memory phase Remember-Studied items required a "yes" response, whereas all other probe-types required a "no" response. Standard error is reported in parentheses.*

	Forget-Recent	New	Remember-Recent	Remember-Studied
Accuracy	0.98 (0.01)	0.99 (0.01)	0.94 (0.02)	0.88 (0.02)
RT	801.14 (28.75)	802.73 (36.42)	837.66 (29.64)	799.36 (35.49)

Next, a repeated-measures Analysis of Variance (ANOVA) examined differences in RTs as a function of negative probe-type. Again, only correct trials were included in our analyses of RT. Results indicated marginally significant differences in RT between the negative probe-types, $F(2, 58) = 2.44$, $p = 0.096$, $\eta_p^2 = 0.08$. Critically, follow-up Bonferroni-corrected pairwise comparisons revealed that participants took longer to correctly reject Remember-Recent probes than they took to correctly reject Forget-Recent probes ($p = .050$). Moreover, once again, RTs for Forget-Recent and New probes did not reliably differ ($p = 1$). These data replicate the findings of Experiment 1 and demonstrate

that PI was virtually eliminated for to-be-forgotten items within working memory. Note, however, that in Experiment 2 the Bonferroni-corrected comparison of RTs for Remember-Recent probes and New probes did not reach significance, $p = .316$. Descriptive statistics of RTs are also reported in Table 3.1. See also Figure 3.2, which depicts the level of PI in the Forget and Remember conditions in Experiment 2.

Long-term Memory. Assessment of long-term memory accuracy revealed the classic directed forgetting effect: Participants had better memory for to-be-remembered items ($M = 0.51$, $SE = 0.04$) than for to-be-forgotten items ($M = 0.36$, $SE = 0.04$), $t(29) = 4.71$, $p < .001$, $r = 0.66$. Accuracy for New probes in long-term memory was also fairly high ($M = 0.83$, $SE = 0.03$). Moreover, a paired-samples t-test comparing A′ sensitivity indicated that participants had worse discriminability for to-be-forgotten items ($M = 0.66$, $SE = 0.03$) than for to-be-remembered items ($M = 0.77$, $SE = 0.02$), $t(29) = 3.51$, $p = .001$, $r = 0.55$, consistent with the directed forgetting effect. Further, participants exhibited no difference in response bias (B″) for to-be-remembered ($M = 0.28$, $SE = 0.06$) and to-be-forgotten items ($M = 0.32$, $SE = 0.06$), $t(29) = 0.84$, $p = .410$, $r = 0.15$. These long-term memory results confirm that directed forgetting in working memory was successfully implemented, and that it leads to deficient long-term memory for the to-be-forgotten items.

Comparison of Short and Long ISIs. Additional analyses were performed to compare the critical measure of RT between Experiment 1 and Experiment 2. A 3 X 2 Mixed ANOVA was conducted on RT as a function of negative probe-type (Forget-Recent, Remember-Recent, or New) and Experiment (Short ISI versus Long ISI). Results indicated a significant main effect of probe-type, $F(2, 116) = 9.23$, $p < .001$. Bonferroni-

corrected pairwise comparisons revealed that participants took significantly longer to reject Remember-Recent probes than Forget-Recent probes ($p < .001$), and they took longer to reject Remember-Recent probes compared to New probes ($p = .004$). There was no difference in RT for Forget-Recent and New probes, $p = 1$. Further, there was no significant main effect of Experiment ($p = .298$), nor was there a significant interaction between Experiment and probe-type ($p = .286$). Thus, these results confirm performance was similar regardless of whether an ISI of 250 ms or 1000 ms was used: Participants consistently demonstrated a reduction in PI for to-be-forgotten items.

Discussion

Experiment 2 replicated the results of Experiment 1: Directed forgetting reduced PI within working memory. Even when the ISI was lengthened between the offset of the six words and the presentation of the forget cue, participants still correctly rejected recent to-be-forgotten items faster than they correctly rejected recent to-be-remembered items. Further, in Experiment 2 the reduction in PI was also observed in accuracy performance. Thus, these data provide further evidence that directed forgetting performed during working memory reduces PI, and that participants are implementing cognitive control in the form of directed forgetting and are not using a delayed encoding strategy to perform the task.

<div align="center">

General Discussion

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Overall, this project assessed the consequences of performing directed forgetting within working memory to determine if it would decrease the magnitude of PI evident for to-be-forgotten items. Results from two experiments indicated that directed forgetting efficiently reduced and virtually eliminated the PI that is typically evident on trial N+1.

Participants displayed significantly less PI for to-be-forgotten lists compared to to-be-remembered lists, and rejected recent to-be-forgotten information as easily as they rejected words that had never previously been presented in the experiment. Despite the well-documented persistent nature of PI, voluntarily controlling the contents of working memory via directed forgetting significantly diminished its occurrence, presumably by reducing the familiarity of to-be-forgotten items to a level comparable to that of previously unseen words.

This reduction in PI parallels the reduction in semantic interference and false memories for to-be-forgotten items following directed forgetting within working memory (Festini & Reuter-Lorenz, 2013). Further, reduced long-term memory of previously to-be-forgotten items compared to to-be-remembered items is consistently observed. Taken together, these results demonstrate that people can voluntarily forget specific memoranda within a canonical working memory task, thereby diminishing the interference effects and long-term memorability of these items. Moreover, Ecker, Lewandowsky, and Oberauer (2013) recently demonstrated that removing targeted information from working memory eliminated item repetition and similarity effects for these items following sufficient delays after presentation of the removal cue. These results thus provide additional evidence for the voluntary forgetting of information in working memory, as well as evidence that to-be-forgotten information is associated with diminished memorial effects.

To explain these results we propose that directed forgetting in working memory operates by reducing the strength of the memory signal of the targeted memoranda. A reduced memory signal may result from selective rehearsal of the to-be-remembered items (e.g., Basden, Basden, & Gargano, 1993), withdrawal of resources from the to-be-

forgotten items (Fawcett & Taylor, 2012), the active inhibition of to-be-forgotten items

(e.g., Fawcett & Taylor, 2008; Zacks, Radvansky, & Hasher, 1996; see also Neumann &

DeSchepper, 1992[12]), or some combination of these processes (see Festini & Reuter-

Lorenz, 2013 for discussion). The present results cannot distinguish among these

hypothetical mechanisms. Nevertheless, our proposal that the memory strength is reduced

for to-be-forgotten items is also informed by the observation that directed forgetting has

consequences for these targeted memory representations that are quite distinct from the

effects of other "memory reducing" manipulations, such as articulatory suppression. In

contrast to the present results, Atkins et al. (2011) demonstrated that articulatory

suppression executed after encoding and during the 3-4 second maintenance interval

increased PI within working memory. Critically, the effects of articulatory suppression

were selective and did not affect performance for positive or non-recent probes. Thus,

interfering with rehearsal did not reduce the items' familiarity or memory strength per se,

but instead may have increased noise, making it more difficult for participants to

associate probe items with their appropriate temporal context. Likewise, Atkins et al.

(2011) found that articulatory suppression *increased* semantic interference and false

working memories (see also Atkins & Reuter-Lorenz, 2008). Directed forgetting seems to

operate quite differently from articulatory suppression. Based on the decreases we have

observed in both semantic and proactive interference, along with reduced gist-based

distortions, and diminished long-term memorability of the to-be-forgotten items, we

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[12] Using a variant of a directed forgetting paradigm in which a switch in the presentation
style of the stimuli indicated that prior stimuli were irrelevant and new stimuli were
relevant, Neumann and DeSchepper (1992) found support for limited capacity spreading
inhibition. Participants took longer to reject words that had previously been irrelevant
distractors, and this effect varied as a function of irrelevant set size, such that the slowest
RTs were for probes that had been the sole distractors (see also Bjork, 1989).

propose that directed forgetting can disrupt the formation and/or maintenance of targeted representations, attenuating their memory signal.

An alternative to the idea that a controlled process decreases the memory strength of to-be-forgotten items is the possibility that membership in a Forget list provides a contextual tag that facilitates subsequent rejection of those items. That is, on each trial, a "Forget" context tag could be assigned to the to-be-forgotten items, and a "Remember" context tag could be assigned to the to-be-remembered items. Participants may more easily reject Forget-Recent probes compared to Remember-Recent probes because a "Forget" context tag is more readily associated with a negative response, in contrast to the "Remember" tag that was previously associated with an affirmative response. While this account is plausible, data from Bissett, Nee, and Jonides (2009) suggest that response selection and interference control are dissociable. They combined a working memory directed forgetting task and a stop-signal task, in which a stop-signal was included after the presentation of a proportion of the probes, and they found that directed forgetting was not influenced by the stop-signal manipulation. But, when they combined a stop-signal task and a go/no-go task, overadditive effects on behavior were observed, suggesting that both tasks were tapping the same underlying mechanism. The fact that directed forgetting was not altered when response inhibition was occasionally required implies that directed forgetting does not operate by biasing responses. Further, we favor the interpretation that directed forgetting attenuates the memorial signal and the accompanying familiarity of to-be-forgotten items, which we believe can more easily explain the similarity in RTs for Forget-Recent and New probes, as well as the long-term recognition results. A reduced memory signal is compatible with the range of effects we have observed (here and in

Festini & Reuter-Lorenz, 2013) on both immediate and delayed measures of explicit

memory as well as more indirect, implicit measures of interference and gist. However, as

we discuss below, additional testing of this hypothesis is needed, along with further

investigation of the means by which reduced memory strength may be achieved.

Relation to Other Attempts to Reduce Proactive Interference

Our results reveal that deliberate control of memory contents can reduce PI effects

that are typically robust from one working memory trial to the next (e.g., Monsell, 1978;

Jonides, & Nee, 2006; Nee, Jonides, & Berman, 2007), whereas at least one prior attempt

was unsuccessful (Berman et al., 2009, Experiment 6). During the instruction phase of

this previous study, Berman et al. gave participants the general instruction to ignore the

prior memory set after each trial had ended. However, in a working memory task, there is

no strategic advantage to retaining the prior memoranda after the probe. Hence, telling

participants not to retain each memory set may merely reinforce what is likely their

default approach to the task, rather than promoting a targeted forgetting strategy. In

contrast, the current paradigm invites participants to forget a designated subset of

information on each trial. Moreover, the forget cue is presented before the retention

interval, at a point in the trial where strategic control of memory can be optimally

engaged in preparation for the upcoming probe event.

The trial-by-trial strategic support provided by our task appears to be more

effective at reducing the across-trial interference (i.e., PI from trial N-1) than the general

pre-task instruction used by Berman et al. (2009). However, we know from our prior

work (Festini & Reuter-Lorenz, 2013) and from other studies of directed forgetting in

working memory (e.g., Nee et al., 2007), that when to-be-forgotten items are presented as

negative probes on the same trial, they are not rejected as readily as new items. We refer to this difficulty in rejecting same-trial to-be-forgotten probes as directed forgetting interference or within-trial PI, which is potentially distinct from across-trial PI induced by recent probes. Our evidence that directed forgetting performed on the contents of working memory can lead to virtual elimination of PI on the *next* trial suggests that something about starting a new trial may help to make forgetting more complete (i.e., time, context change, interference from a new memory set, re-engagement of memory control). However, the fact that PI persists across trials for to-be-remembered items underscores that the deliberate control of memory in response to the forget cue, and not merely the presentation of a new memory set, decreases the memorability and PI from to-be-forgotten items.

Our results thus add to the long-term directed forgetting work, which also documents decreases in PI. In long-term memory, PI reduction is evidenced by the directed forgetting benefit: superior memory for to-be-remembered information when half of the words can be forgotten compared to a control condition in which all of the information must be remembered (e.g., Bjork, 1970; 1989). This improvement in memory for to-be-remembered items is thought to result because of reduced PI from forgotten items in long-term memory. Bäuml and Kliegl (2013) further established that directed forgetting, interpolated testing, and context change instructions all reduced PI within long-term memory, and they argue that this decrease in PI is due to a reduced search set size for target items (see also Pastötter & Bäuml, 2007, 2010; Sahakyan & Kelley, 2002). Moreover, a handful of other long-term memory methods have demonstrated successful PI reduction. For instance, a release from PI has consistently been shown when the

semantic context of the current list is changed from that of prior lists (e.g., Wickens, 1970). Further, Jacoby, Wahlheim, Rhodes, Daniels, and Rogers (2010) demonstrated that PI could be reduced with experience. When participants were given multiple study-test episodes, PI was diminished on the second round (see also Wahlheim & Jacoby, 2011). In a follow-up experiment, they demonstrated that this reduction in PI with prior experience was partially due to increased attention to the switched word-pairs, as indexed by lengthened study times in a self-allocated study time procedure. Thus, prior experience with PI reduced the subsequent PI that was induced in long-term memory due to different encoding strategies.

Relation to the Work of Edward E. Smith

Edward E. Smith contributed substantially to the study of interference control in working memory, and we are honored to contribute this report in his memory. Ed Smith was one of the lead scientists in several key papers that invigorated research interest in understanding the role of executive functions in working memory and identifying their neural underpinnings. Especially relevant to this report, he and his colleagues established that the left inferior frontal gyrus was associated with interference resolution in the recent probes variant of the item-recognition task (Jonides et al., 1998). Further, in collaboration with Jonides, Reuter-Lorenz, and their team, he documented age-differences in the efficiency of interference resolution reflected in greater PI for older adults and linked this deficit to ineffective recruitment of left inferior frontal cortex (Jonides et al., 2000). Moreover, his insights were invaluable to the team's neuroimaging work demonstrating that the resolution of PI was neurally dissociable from the resolution of response conflict in a variant of the recent probes task that pitted these two types of interference against

one another (Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003). Ed Smith's body of work on executive functions and working memory provided empirical and theoretical foundation for the questions addressed here about the potential for controlled mitigation of PI in working memory.

Particularly pertinent to the present project, Smith et al. (2011) examined the ability of individuals with schizophrenia to perform directed forgetting within working memory. When compared to healthy control participants, patients with schizophrenia were worse at following the forget instruction, exhibiting differentially lengthened RTs to correctly reject to-be-forgotten probes. Performance on the directed forgetting task was also compared to performance on a perceptual selection task, where participants were cued what to remember *before* the presentation of the stimuli. Interestingly, patients with schizophrenia performed similarly to healthy controls on the perceptual selection task and only differed in the directed forgetting condition. Thus, these results demonstrate that cognitively controlling the contents of working memory via directed forgetting is impaired by schizophrenia. This conclusion was corroborated by converging neuroimaging evidence that also indicated less effective forgetting in schizophrenia (Eich, Nee, Insel, Malapani, & Smith, 2013). In light of the present findings, we might further predict that individuals with schizophrenia would not demonstrate the beneficial effects of directed forgetting in the form of reduced PI for to-be-forgotten information, nor a reduced directed forgetting effect in long-term memory.

Future Directions

The focus of the present experiments was to investigate the effects of the cognitive control of familiarity. Although these experiments successfully establish the

previously undocumented reduction of proactive interference in working memory following directed forgetting, we acknowledge several limitations. First, these experiments were designed to examine the consequences of directed forgetting in working memory but not the mechanisms that lead to its success. Candidate mechanisms include selective rehearsal and active inhibition (e.g., Fawcett & Taylor, 2012; Festini & Reuter-Lorenz, 2013), and follow-up experiments should be conducted to test how directed forgetting is implemented within working memory. Unlike in list-method long-term directed forgetting, the current working memory lists are presented concurrently. Therefore, any forgetting that results from sequential presentation of to-be-forgotten and to-be-remembered lists (i.e., Pastötter & Bäuml, 2010) is unlikely to play a major role in directed forgetting as performed in the current paradigm. Nevertheless, it is possible that these types of list-method mechanisms may contribute to implicit across-trial directed forgetting, which future studies could be designed to assess. Further, the present experiments lack an additional baseline condition with which to compare the level of proactive interference for to-be-remembered and to-be-forgotten items. Including an additional encode-only condition would allow one to determine if proactive interference increases for to-be-remembered items, decreases for to-be-forgotten items, or both, when compared to words that were encoded but not dealt with further.

Finally, by using functional magnetic resonance imaging (fMRI) and by modifying our task to assess both within-trial and across-trial PI, we could simultaneously examine the neural underpinnings of the processes that control these forms of interference. Prior work indicates that the left inferior frontal gyrus (IFG) is involved in resolving proactive interference induced from recent probes (e.g., Jonides et

al., 1998; Nee et al., 2007), as well as in memorial selection following directed forgetting (e.g., Nee & Jonides, 2009; Eich et al., 2013). As such, we would expect to see reduced left IFG activation to Forget-Recent probes compared to Remember-Recent probes, as well as left IFG activation in response to within-trial to-be-forgotten probes. Moreover, work from Anderson et al. (2004) using the Think/No-Think task indicates that the dorsolateral prefrontal cortex (DLPFC) contributes to the suppression of long-term memories and results in reduced hippocampal activation. Based on these findings, we might similarly expect reduced hippocampal activation for to-be-forgotten items. Moreover, fMRI could be used to analyze the neural systems involved at the onset of the forget cue compared to the onset of a control cue, which may reveal DLPFC recruitment. This type of imaging work would complement our characterization of the behavioral effects of directed forgetting in working memory, and would assist in the understanding of how people voluntarily perform this type of cognitive control.

Conclusions

Critically, the current studies demonstrate that directed forgetting performed during working memory decreases PI for to-be-forgotten items. Participants correctly rejected recent to-be-forgotten probes more efficiently than they rejected recent to-be-remembered probes. Further, the results from Experiment 2 argue against a delayed encoding strategy, and favor the view that participants are implementing cognitive control in the form of directed forgetting. The observed reduction in proactive interference is consistent with the reduction in semantic interference and false memories following directed forgetting in working memory (Festini & Reuter-Lorenz, 2013). In combination, these results indicate the effectiveness of directed forgetting implemented

within working memory, which we propose to work by attenuating the memory representations of to-be-forgotten items. Future research can be aimed at elucidating the neural and cognitive mechanisms by which directed forgetting exerts these memorial effects and investigating the translational utility of this manipulation, along with potential benefits of directed forgetting in real-life contexts.

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Chapter 4: Examining the Role of Rehearsal in Directed Forgetting within Working

Memory

Abstract

Directed forgetting instructions ask people to forget targeted memory representations. In the context of working memory, people attempt to forget representations that are currently held in mind. Here, we examined the role of rehearsal in directed forgetting within working memory, by (1) testing the influence of articulatory suppression on directed forgetting efficiency, and by (2) assessing the ability of people to perform forgetting in the absence of other to-be-remembered competitors to rehearse. In Experiment 1, articulatory suppression interfered with directed forgetting, increasing the proportion of false alarms to to-be-forgotten probes in the working memory phase and decreasing the magnitude of the long-term directed forgetting effect. Experiment 2 tested whether the simultaneous rehearsal of to-be-remembered items was necessary to exert forgetting. Long-term memory accuracy demonstrated equivalent forgetting regardless of whether or not participants were required to simultaneously rehearse to-be-remembered items. Experiment 3 combined the manipulations from the first two experiments to determine if articulatory suppression also interfered with forgetting when competitors to remember were absent. Results confirmed that articulatory suppression interfered with directed forgetting and that participants were as efficient at directed forgetting with and without competitors to remember. In combination, these experiments suggest that directed forgetting in working memory requires an active control process that is limited

by articulatory suppression, and that forgetting can be performed efficiently regardless of whether additional to-be-remembered items are present.

Introduction

Strategically controlling the contents of memory can enable people to preferentially remember and forget specific information. For instance, people could decide to remember important information (i.e., names, dates, conversations) or positive life events (i.e., details of weddings, birthdays), and they could similarly decide to deliberately forget unimportant information (i.e., irrelevant details) or negative life events (i.e., emotionally traumatic experiences). In the laboratory, conscious control of memory is often studied using the directed forgetting paradigm, in which participants are cued to remember and to forget specific information. The majority of research on directed forgetting has focused on a long-term memory (LTM) context; consequently, the properties and mechanisms of directed forgetting performed during working memory (WM) are less well understood. Our own prior work has demonstrated that directed forgetting within working memory is successful, such that it reduces memorial interference within working memory and also reduces long-term veridical memory (Festini & Reuter-Lorenz, 2013, 2014). To begin to address mechanistic questions for *how* this form of memory control operates, the goal of the current project was to investigate the role of rehearsal in directed forgetting within working memory.

Assessment of directed forgetting in working memory involves the use of a modified item-recognition paradigm (e.g., Sternberg, 1966), in which the experimenters first present participants with sub-span sets of stimuli to encode. Unlike classic delayed-recognition tasks, however, after initial encoding, the stimuli disappear and then a cue

signals which subset of items should be forgotten and which subset of items should be remembered (e.g., Festini & Reuter-Lorenz, 2013, 2014; Nee & Jonides, 2008, 2009; cf. Oberauer, 2001, 2005). After a retention interval of several seconds, participants are shown a probe item, and they must decide whether or not it was one of the to-be-remembered items. This task allows for the assessment of both response time (RT) and accuracy for probe items that were to-be-remembered, to-be-forgotten, or new.

Prior work has demonstrated that participants take longer to correctly reject a probe item that was a member of the to-be-forgotten set than they take to correctly reject a new item that has not been seen for at least several trials (e.g., Nee & Jonides, 2008, 2009). We term this phenomenon *directed-forgetting interference*, and we identify this as one of the quintessential effects observed following the voluntary control of working memory. Further, although people are frequently capable of indicating that members of the to-be-forgotten list are not part of the current to-be-remembered memory set, they occasionally make errors and mistakenly endorse to-be-forgotten probes. Consequently, individuals also tend to exhibit more false alarms to Forget probes than New probes during working memory directed forgetting tasks (e.g., Nee & Jonides, 2008).

Moreover, we further characterized the short- and long-term memorial effects of controlling the contents of working memory in two recent papers. First, we demonstrated that directed forgetting reduces semantic interference and false memories across short- and long-delays (Festini & Reuter-Lorenz, 2013). Our paradigm included the presentation of associatively-related probe words, which allowed for the evaluation of semantic interference and semantic intrusions in memory. Additionally, our paradigm included a surprise recognition memory test after participants completed all of the working memory

trials (as in Flegal, Atkins, & Reuter-Lorenz, 2010). This surprise long-term memory test enabled us to determine whether performing directed forgetting within the context of working memory also influenced long-term memory. Critically, in this long-term recognition test, participants now needed to indicate whether they saw each word before, no matter if it was previously to-be-remembered or previously to-be-forgotten. Our results documented the classic LTM directed forgetting effect (DF effect) such that participants had better memory for words that were previously designated as to-be-remembered rather than those that were designated as to-be-forgotten, indicating that controlling the contents of working memory also influences the long-term memorability of these items.

In a complementary paper, we investigated whether directed forgetting instructions could similarly reduce recency-induced proactive interference within working memory (Festini & Reuter-Lorenz, 2014). In two experiments, using a modified item-recognition directed forgetting task, with the occasional presentation of recent probes (i.e., probes from the *prior* memory set, not the current memory set), we documented that participants had less proactive interference for recent to-be-forgotten words than for recent to-be-remembered words. Further, we replicated our finding of reduced long-term memorability of to-be-forgotten items in this paradigm as well.

Finally, a distinct working memory paradigm that required participants to remove and update specific information yielded further evidence of the successful control of working memory. Ecker, Lewandowsky, & Oberauer (2013) demonstrated that item repetition and similarity effects were diminished for to-be-removed representations when there was a sufficient delay following the presentation of the removal cue. These results

thus provide converging evidence that individuals are able to remove items from working memory, and that this control leads to reduced memorial effects.

Taken together, we posit that voluntarily controlling the contents of working memory results in the attenuation of memory representations of to-be-forgotten items, which we feel is compatible with the set of results that we and others have observed. Nevertheless, the mechanisms underlying *how* directed forgetting is implemented within working memory are not yet understood. Long-term memory directed forgetting paradigms often propose differential rehearsal as a contributing mechanism (e.g., Basden, Basden, & Gargano, 1993; MacLeod, 1975; Sheard & MacLeod, 2005; Shebilske, Wilder, & Epstein, 1971). However, the role of rehearsal in directed forgetting in working memory has not yet been specifically tested. Therefore, the goal of the current set of experiments is to examine the role of rehearsal in directed forgetting within working memory by (1) assessing the consequences of introducing an articulatory suppression manipulation, and by (2) testing the efficiency of directed forgetting within working memory when simultaneously included to-be-remembered items are not present to rehearse. Results from these experiments will begin to address how the voluntary control of working memory is implemented.

Experiment 1

Experiment 1 was designed to test the impact of articulatory suppression (AS) on directed forgetting in working memory. Specifically, some participants were required to repeat the word "the" during each trial in an effort to disrupt sub-vocal rehearsal (e.g., Baddeley, Thomson, & Buchanan, 1975; Levy, 1971; Murray, 1968). If selective rehearsal of to-be-remembered items promotes forgetting, then articulatory suppression

should disrupt forgetting by impeding rehearsal of these items. We also note that the requirement to perform AS introduces a secondary task in addition to directed forgetting. Consequently, articulatory suppression may also *interfere* with forgetting if directed forgetting involves an active control process, as the requirement to perform articulatory suppression may tax the executive resources necessary to perform effortful forgetting (cf. Fawcett & Taylor, 2008; Wylie, Foxe, & Taylor, 2008). Alternatively, requiring articulatory suppression may *help* directed forgetting in working memory by preventing any inadvertent rehearsal of to-be-forgotten items. If forgetting is solely the result of reduced rehearsal of to-be-forgotten memoranda, then articulatory suppression should assist forgetting by helping disrupt rehearsal of these items. Experiment 1 tests these alternatives by observing the efficiency of directed forgetting with concurrent articulatory suppression. Of critical importance, we assess the false alarm rate for to-be-forgotten probes in the working memory task phase as well as the long-term directed forgetting effect to determine if articulatory suppression helps or hinders forgetting.

Method

      Participants. Ninety participants (62 women) volunteered to participate in this study. Participants ($M = 18.60$ years, $SE = 0.08$) received \$10.00 or course credit for their participation and were treated within the ethical guidelines of the American Psychological Association. Fifteen additional subjects were run and excluded for the following reasons: eight participants were excluded because they reported not studying all of the words, three participants were excluded due to working memory accuracy that fell 2.5 standard deviations below the mean, three participants failed to respond on multiple trials, and one participant reported only studying the first letter of each word.

Materials. Words were selected from the MRC database (http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm). All of the words had the following characteristics: 3 to 8 letters, 1 to 3 syllables, Kucera & Francis written frequency of 10-150, familiarity of 400-650, and concreteness rating of 300-600. A unique set of words was presented on every trial, with each participant viewing a total of 288 words.

Procedure. This experiment implemented a working memory directed forgetting task (e.g., Festini & Reuter-Lorenz, 2013, 2014; Nee, Jonides, & Berman, 2007; Nee & Jonides, 2008; Zhang, Leung, & Johnson, 2003). See Figure 4.1 for a task diagram. On each trial, two lists of three words were presented, one list on either side of a fixation cross. Participants studied these six words for 3 seconds. After the study phase and an inter-stimulus interval (ISI) of 250 milliseconds, a forget cue appeared, positioned randomly to the left or right of fixation, for 2 seconds, indicating which list the participant was supposed to forget. This was followed by a 3-second retention interval. Critically, two-thirds of participants ($n = 60$) performed articulatory suppression during this interval by repeating the word "the" aloud, while one-third of participants did not ($n = 30$). We parametrically varied the onset of articulatory suppression to determine if beginning articulatory suppression later in the trial lead to less pronounced effects. Of the participants who performed articulatory suppression, half ($n = 30$) started saying the word "the" as soon as the forget cue appeared and continued saying "the" during the retention interval, and the other half ($n = 30$) only said "the" during the retention interval, amounting to 2 less seconds of AS per trial. We refer to this latter group as the articulatory suppression late (AS Late) group. The other two groups were termed the No

AS group and the AS group. After the retention interval, a single recognition probe appeared in the center of the screen, and the participant then indicated via a mouse button press whether or not that probe was included in the set of to-be-remembered words. Participants were instructed to make this response as quickly and accurately as possible. An inter-trial interval (ITI) of 1500 milliseconds preceded the next set of six words.

Each probe word could be one of three different probe-types. Probes that were included in the set of to-be-remembered words are referred to as "Remember" probes. These probes require an affirmative response because they were members of the to-be-remembered memoranda. Probe words that were included on the to-be-forgotten side of the screen are called "Forget" probes. Because these probes were not members of the to-be-remembered memoranda, Forget probes require a negative response. Finally, some probes were never previously presented. These probes are referred to as "New" probes and require a negative response. The response rate for the task was set at 50% affirmative responses and 50% negative responses. Thus, there were 24 Remember probes, 12 Forget probes and 12 New probes, yielding a total of 48 trials in the working memory phase. Participants completed 12 practice trials before beginning the experimental trials, and the probe rate in the practice trials was consistent with that in the actual task.

The stimuli were balanced following several guidelines. First, all words were trial unique—no words were repeated throughout the experiment. Further, importantly, each probe word was presented as each probe-type between-subjects (i.e., the probe word "THROW" was to-be-remembered for some individuals, to-be-forgotten for some individuals, and new for other individuals). Moreover, the forget cue appeared equally often on either side of the screen, and the probe word originated from each of the three

list positions equally often. These counterbalanced trials were presented in random order

using EPrime software (Psychology Software Tools, Inc.).
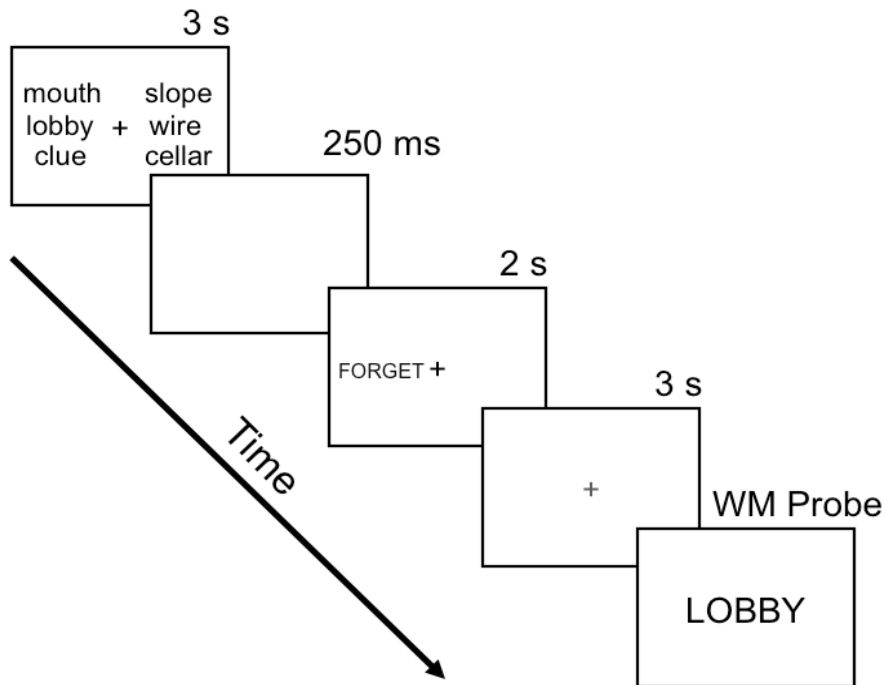
Figure 4.1 *Diagram of the directed forgetting task as implemented in Experiment 1. One-third of participants saw a green cross ("+") presented concurrently with the forget cue and that remained on the screen during the retention interval. These participants had to perform articulatory suppression (AS) during this entire 5-second interval (AS condition). One-third of participants only saw the green cross during the 3-second retention interval and only had to perform articulatory suppression during this time (AS Late condition). One-third of participants never saw a green cross and never had to perform articulatory suppression (No AS condition). In this example, the probe word "LOBBY" is a Forget probe. Participants should indicate that "no" it was not one of the words they were supposed to remember by clicking the right mouse button.*

After completing the WM trials, participants performed a surprise LTM

recognition test. For this test, individuals viewed words presented one at a time for a

maximum of 4000 ms (termination upon response; ITI = 1750 ms) and were asked to

indicate whether or not they had studied the word before—no matter if it was previously

to-be-forgotten or to-be-remembered. These instructions parallel the standard LTM

directed forgetting instructions (e.g., see MacLeod, 1998). Like the WM probes, the LTM

probes could be one of the three probe-types: Forget, Remember, or New. None of the

words probed in LTM were previously probed in WM. The probe rate was consistent

with the WM task: 50% negative and 50% positive probes. Thus, in the LTM recognition

test, there were 24 New probes, 12 Remember probes, and 12 Forget probes. Notably, in

LTM, Forget probes now required a "Yes" response. These LTM positive probes were

originally presented equally often on each side of the screen and equally often in each of

the three list positions in the WM phase. Further, the LTM positive probes were balanced

such that they equally often originated from a WM trial that had previously received a

New, Remember, or Forget probe. This long-term memory test allowed us to ascertain

the effectiveness of performing directed forgetting within working memory in all AS

conditions. Successful implementation of directed forgetting would result in inferior

long-term memory of to-be-forgotten items and superior long-term memory of to-be-

remembered items.

Results

   Working Memory. Working memory performance was fairly accurate for both

positive probes ($M = 0.84$, $SE = 0.01$) and negative probes ($M = 0.88$, $SE = 0.01$),

although a Wilcoxon Signed Ranks Test[13] revealed that participants were significantly

more accurate for negative probes than positive probes, $z = 3.45$, $p = .001$, $r = 0.36$[14].

Further, a Kruskal-Wallis test indicated that participants exhibited significant differences

in accuracy depending on their AS condition, $\chi^2(2) = 8.54$, $p = .014$. Follow-up Mann-

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[13] Nonparametric tests were used due to non-normal distributions, when appropriate.
[14] The statistic "r" is a measure of effect size, calculated as indicated by Rosenthal
(1991).

Whitney tests revealed that participants were significantly more accurate in the No AS condition ($M = 0.90$, $SE = 0.01$) as compared to the AS ($M = 0.85$, $SE = 0.01$) and AS Late conditions ($M = 0.85$, $SE = 0.01$), $z = 2.52$, $p = .012$, $r = 0.33$, and $z = 2.53$, $p = .011$, $r = 0.33$, respectively. There were no significant differences in accuracy between the AS and AS Late conditions, $z = 0.05$, $p = .959$, $r = 0.01$. See Table 4.1 for descriptive statistics of accuracy for each probe-type.

Table 4.1 *Mean accuracy and mean response time (RT) in Experiment 1 as a function of probe-type and articulatory suppression (AS) condition in working memory. Mean RTs are reported in milliseconds. Only correct responses are included in the RT average. Note that in the working memory phase Remember probes required a "yes" response, whereas Forget and New probes required a "no" response. Standard error is reported in parentheses.*

		Forget	New	Remember
Accuracy	No AS	0.86 (0.02)	0.99 (0.00)	0.85 (0.02)
	AS	0.78 (0.03)	0.96 (0.02)	0.82 (0.02)
	AS Late	0.74 (0.03)	0.98 (0.01)	0.84 (0.02)
RT	No AS	1005.52 (45.70)	775.44 (28.53)	872.78 (36.72)
	AS	1218.51 (68.89)	980.48 (53.65)	1057.55 (53.90)
	AS Late	1134.52 (44.78)	891.98 (29.73)	984.89 (37.58)

Next we examined the influence of articulatory suppression on working memory performance by analyzing false alarms to negative probes and accuracy to positive probes separately. First, participants were consistently accurate for Remember probes in all three AS conditions, $\chi^2(2) = 0.77$, $p = .681$. Thus, articulatory suppression did not influence WM accuracy of to-be-remembered probes. Next, a mixed analysis of variance (ANOVA) was conducted on the proportion of false alarms to negative probes as a

function of probe-type (Forget or New) and AS condition (No AS, AS, or AS Late).

Results revealed a significant main effect of probe-type, $F(1, 87) = 134.70$, $p < .001$, η_p^2

$= 0.608$, such that participants made significantly more false alarms to Forget probes than

New probes. There was also a significant main effect of articulatory suppression, $F(2, 87)$

$= 6.25$, $p = .003$, $\eta_p^2 = 0.126$, which was qualified by a significant interaction, $F(2, 87) =$

4.12, $p = .019$, $\eta_p^2 = 0.087$. Follow-up Kruskal-Wallis tests indicated that this interaction

occurred because AS significantly increased false alarms to Forget probes, $\chi^2(2) = 13.29$,

$p = .001$, but AS did not significantly affect false alarms to New probes, $\chi^2(2) = 4.60$, $p =$

.100. Thus, articulatory suppression differentially impaired forgetting, significantly

increasing false alarm rates for to-be-forgotten probes but not for new probes. Additional

follow-up Mann-Whitney tests revealed that participants made more false alarms to

Forget probes in the AS and AS Late conditions relative to the No AS condition, $z = 2.68$,

$p = .007$, $r = 0.35$, and $z = 3.40$, $p = .001$, $r = 0.44$, respectively. However, there were no

significant differences in false alarms to Forget probes in the AS and AS Late conditions,

$z = 1.12$, $p = .263$, $r = 0.14$. Thus, both the AS and AS Late manipulations impaired

forgetting relative to the No AS condition, but there was no significant difference

between performance in the AS and AS Late conditions. See Figure 4.2.

WM: Mean Proportion False Alarms
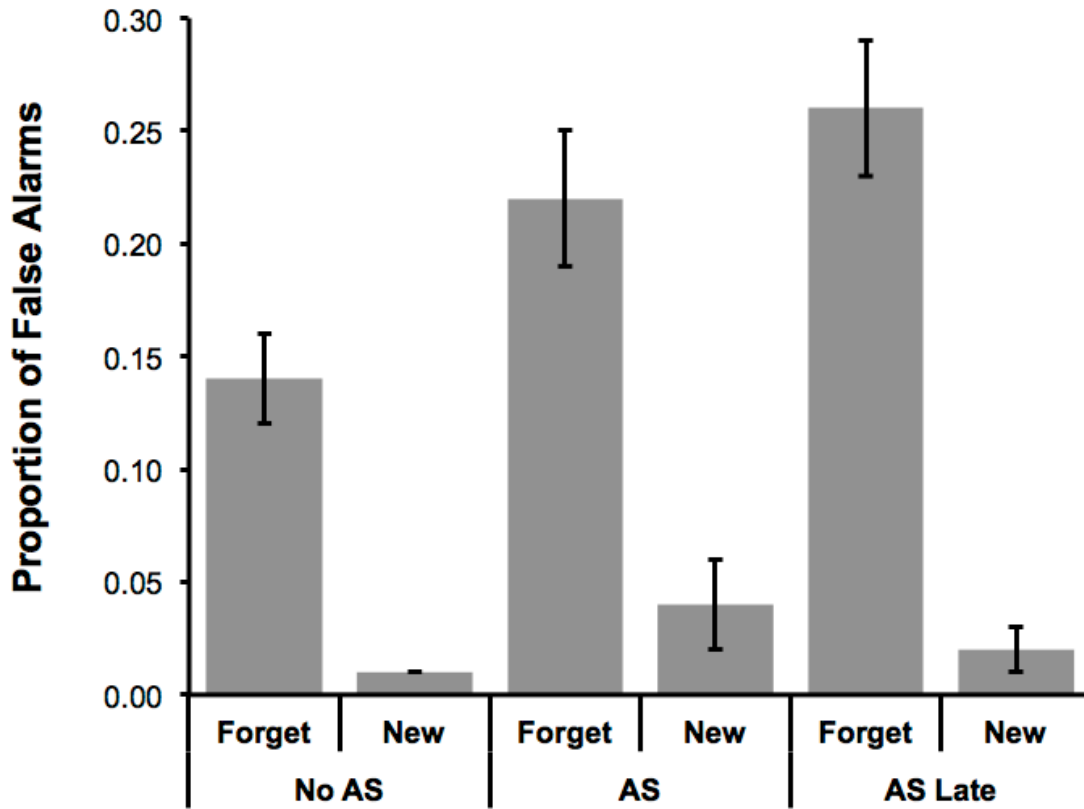
Figure 4.2 *Mean proportion of false alarms (± standard error) to Forget and New probes for each articulatory suppression (AS) condition: No AS, AS, or AS Late. Participants exhibited differentially greater false alarms to Forget probes with added AS.*

Next, we assessed the influence of articulatory suppression on response times (RTs) to correctly reject Forget and New probes. A mixed ANOVA revealed a significant main effect of probe-type, $F(1, 87) = 170.64$, $p < .001$, $\eta_p^2 = 0.662$: participants took significantly longer to correctly reject Forget probes than New probes. There was also a significant main effect of AS condition, $F(2, 87) = 5.55$, $p = .005$, $\eta_p^2 = 0.113$, such that articulatory suppression lengthened RTs. However, there was no significant interaction between probe-type and AS condition, $F(2, 87) = 0.04$, $p = .96$, $\eta_p^2 = 0.001$. Paired-

samples t-tests indicated that participants consistently exhibited lengthened RTs to Forget probes relative to New probes without AS, $t(29) = 8.54$, $p < .001$, $r = 0.84$, with AS, $t(29) = 6.99$, $p < .001$, $r = 0.79$, and with AS Late, $t(29) = 7.40$, $p < .001$, $r = 0.81$. Thus, directed forgetting interference evident in RTs was not significantly impacted by our articulatory suppression manipulation. Note that RTs also lengthened for Remember probes with the addition of articulatory suppression, $F(2, 87) = 4.59$, $p = .013$. Descriptive statistics of RTs are included in Table 4.1.

Long-term Memory. The surprise long-term memory recognition test allowed us to ascertain whether performing articulatory suppression during working memory facilitated, interfered with, or did not influence the long-term memorability of to-be-forgotten items relative to to-be-remembered items. In the long-term memory test, participants were asked to indicate whether or not they studied each probe word before, no matter if it was previously to-be-remembered or to-be-forgotten.

A mixed ANOVA was conducted comparing long-term recognition accuracy as a function of probe-type (Forget or Remember) and working memory AS condition (No AS, AS, AS Late). Results revealed a significant main effect of probe-type, $F(1, 87) = 13.83$, $p < .001$, $\eta_p^2 = 0.137$, indicating that, in general, participants had better memory for to-be-remembered items than to-be-forgotten items. However, there was no significant main effect of AS condition, $F(2, 87) = 0.51$, $p = .602$, $\eta_p^2 = 0.012$, suggesting that the inclusion of AS during WM did not lower long-term memory accuracy overall. Yet, importantly, there was a marginally significant interaction between probe-type and AS condition, $F(2, 87) = 2.81$, $p = .066$, $\eta_p^2 = 0.061$. Follow-up paired samples t-tests demonstrated that this marginal interaction occurred because there was a significant

difference in accuracy between Forget and Remember probes in the No AS condition, $t(29) = 4.86$, $p < .001$, $r = 0.67$, but there were no significant differences in accuracy between the Forget and Remember probes in the AS and AS Late conditions, $t(29) = 1.12$, $p = .274$, $r = 0.20$, and $t(29) = 1.09$, $p = .284$, $r = 0.20$, respectively. A further analysis directly comparing the magnitude of the DF effect between the AS conditions confirmed that there were significantly reduced DF effects for the AS condition and the AS Late condition when compared to the No AS condition, $t(58) = 2.21$, $p = .031$, $r = 0.28$, and $t(58) = 2.04$, $p = .046$, $r = 0.26$, respectively. But there was no significant difference in the magnitude of the DF effect between the AS and AS Late conditions, $t(58) = 0.09$, $p = .931$, $r = 0.01$. Moreover, one-sample t-tests comparing the magnitude of the DF effects to zero revealed a significant DF effect without AS, $t(29) = 4.86$, $p < .001$, $d = 0.89$, but no significant DF effects for the AS or AS Late conditions, $t(29) = 1.12$, $p = .274$, $d = 0.20$, and $t(29) = 1.17$, $p = .250$, $d = 0.21$. Thus, from these results, it is evident that performing articulatory suppression during working memory significantly interfered with forgetting, minimizing the long-term memory directed forgetting effect. Descriptive statistics are reported in Table 4.2.

Table 4.2 *Mean long-term memory accuracy in Experiment 1 as a function of probe-type and articulatory suppression (AS) condition. Note that in the long-term memory phase both Forget and Remember probes required a "yes" response, whereas New probes required a "no" response. Standard error is reported in parentheses.*

	Forget	Remember	New
No AS	0.37 (0.03)	0.54 (0.03)	0.78 (0.02)
AS	0.39 (0.03)	0.44 (0.05)	0.74 (0.03)
AS Late	0.43 (0.03)	0.48 (0.04)	0.75 (0.03)

Moreover, a one-way ANOVA revealed no significant differences in false alarms to New probes in long-term memory for the No AS, AS, and AS Late conditions, $F(2, 87) = 0.74$, $p = .480$. This result indicates that the articulatory suppression manipulation did not alter false alarms to these control probes and only impacted recognition performance for the critical probe words. Further, this false alarm rate of 24% for new probes is consistent with the false alarm rates we, and others, have observed after incidental encoding (e.g., Festini & Reuter-Lorenz, 2014; Stark & Okado, 2003).

Finally, for the LTM recognition test, we computed A′ and B″—nonparametric indices of sensitivity and response bias, respectively (see Snodgrass & Corwin, 1988; Stanislaw & Todorov, 1999). A mixed ANOVA on A′ as a function of probe-type (Remember or Forget) and AS Condition (No AS, AS, AS Late) revealed a significant main effect of probe-type, $F(1, 87) = 5.07$, $p = .027$, $\eta_p^2 = 0.055$, as well as a marginally significant interaction, $F(2, 87) = 2.37$, $p = .099$, $\eta_p^2 = 0.052$. Follow-up paired samples t-tests indicate that this marginal interaction occurred because participants exhibited reduced sensitivity for Forget probes compared to Remember probes in the No AS condition, $t(29) = 4.08$, $p < .001$, $r = 0.60$, but they did not exhibit differences in sensitivity for Remember and Forget probes in the AS or AS Late conditions, $t(29) = 0.10$, $p = .918$, $r = 0.02$, and $t(29) = 0.72$, $p = .480$, $r = 0.13$, respectively. This finding is consistent with our long-term memory accuracy analyses demonstrating that articulatory suppression interfered with forgetting, and thus yielded sensitivity that was similar for to-be-forgotten and to-be-remembered items in the AS conditions. We also compared response bias (B″) for to-be-forgotten and to-be-remembered probes in the three AS conditions. A mixed ANOVA indicated that there were no differences in response bias

between to-be-remembered and to-be-forgotten items, $F(1, 87) = 0.74$, $p = .391$, $\eta_p^2 = 0.008$. Further, there was no significant influence of AS on response bias, $F(2, 87) = 0.28$, $p = .759$, $\eta_p^2 = 0.006$, nor was there a significant interaction, $F(2, 87) = 0.59$, $p = .559$, $\eta_p^2 = 0.013$. Thus, response bias was consistent for to-be-remembered and to-be-forgotten probes in all AS conditions.

Discussion

This experiment tested the role of rehearsal in directed forgetting within working memory by disrupting the ability to perform sub-vocal rehearsal. Specifically, we manipulated whether or not participants were required to perform articulatory suppression, and we tested whether this rehearsal-impairing requirement helped or hindered forgetting. Rehearsal suppression may have assisted forgetting by reducing rehearsal of to-be-forgotten items. Alternatively, if rehearsal of to-be-remembered items assists forgetting and/or if executive resources were required to implement directed forgetting, then articulatory suppression may have hindered forgetting. Results from Experiment 1 support the latter alternative—articulatory suppression interfered with directed forgetting in working memory. Individuals exhibited significantly more false alarms to to-be-forgotten probes within working memory in the AS conditions, and this effect was differentially observed for to-be-forgotten probes and not for new or to-be-remembered probes. Moreover, assessment of long-term memory accuracy further confirmed that directed forgetting was less efficient with AS. Participants did not exhibit significant long-term directed forgetting effects with the inclusion of AS during working memory. Consistent with this finding, greater sensitivity for to-be-remembered probes was only observed in the No AS condition: when AS was required long-term memory

sensitivity for to-be-remembered and to-be-forgotten probes did not differ. Thus, these results indicate that AS interfered with directed forgetting in working memory.

Although these results clearly indicate that articulatory suppression interfered with forgetting efficiency, the present experiment cannot address *why* articulatory suppression interfered. We posit that articulatory suppression may have disrupted several possible candidate mechanisms of directed forgetting in working memory, which we discuss in turn. First, (1) directed forgetting in working memory may rely on the selective rehearsal of to-be-remembered items (cf. Basden et al., 1993; Bjork, 1972; MacLeod, 1975; Woodward, Park, & Seebohm, 1974), and the requirement to perform AS may have interfered with the efficiency of this process, contributing to the decline in forgetting effectiveness. Next, (2) directed forgetting in working memory may rely on the ability to differentiate which lists are to-be-remembered and to-be-forgotten (cf. Bjork, 1970, 1972). Requiring AS may have interfered with participants' ability to distinguish each item's list-membership, and impaired set differentiation may have contributed to poorer forgetting. Further, we posit that (3) directed forgetting in working memory may rely on the controlled inhibition of the to-be-forgotten items (cf. Anderson & Green, 2001; Fawcett & Taylor, 2008; Zacks & Hasher, 1994). The AS manipulation may have taxed the executive resources necessary to perform active inhibition, leading to the observed results. Finally, although our results demonstrate that disrupting sub-vocal rehearsal with articulatory suppression did not assist with forgetting, this does not entirely rule out a rehearsal cessation mechanism of to-be-forgotten items. Indeed, it is important to note that (4) directed forgetting in working memory could require the *active* withdrawal of rehearsal from to-be-forgotten items (cf. Fawcett & Taylor, 2008).

To begin assessment of these potential mechanisms of directed forgetting in working memory, in the next experiment, we test the selective rehearsal of to-be-remembered items account (i.e., the first mechanism that was outlined previously). In particular, we assess whether selective rehearsal of to-be-remembered items is necessary for efficient directed forgetting in working memory.

Experiment 2

The goal of Experiment 2 was to examine the effectiveness of directed forgetting with and without the presence of competitors to remember. If directed forgetting requires the selective rehearsal of to-be-remembered items, then participants should exhibit better forgetting when to-be-remembered items are simultaneously presented. In this case, to-be-remembered items may serve as thought substitutions—places to direct attention away from to-be-forgotten items. Alternatively, the simultaneous presentation of to-be-remembered items may hinder forgetting, and participants may more efficiently forget items when they do not need to commit additional to-be-remembered items to memory. In this case, the requirement to process to-be-remembered items might disrupt forgetting by introducing a secondary task. Finally, directed forgetting may be as efficient with and without the simultaneous presentation of competitors to remember, which would indicate that selective rehearsal of to-be-remembered items is not necessary to voluntarily control the contents of working memory. Experiment 2 tests these three possible outcomes by manipulating whether items to forget were originally presented in isolation or with competitors to remember and assessing the long-term efficiency of this forgetting.

Method

Participants. Thirty-six new participants (18 women) volunteered to participate in this study. Participants (*M* = 19.56 years, *SE* = 0.27) received course credit for their participation and were treated within the ethical guidelines of the American Psychological Association. Eight additional subjects were excluded for the following reasons: four participants were excluded because their working memory performance fell below 2.5 standard deviations of the mean, two participants were excluded due to long-term memory performance that fell below 2.5 standard deviations of the mean, one participant reported not studying all of the words, and one participant was excluded due to being a non-native English speaker.

Materials. Words were selected from the MRC database, and had the same characteristics as those in Experiment 1. A unique set of words was presented on every trial, with each participant viewing a total of 240 words.

Procedure. This experiment was similar to that implemented in Experiment 1, with several key modifications. See Figure 4.3 for a task diagram. On each trial, two lists of three stimuli were presented, one list on either side of a fixation cross. Participants studied these stimuli for 3 seconds. After the study phase and an ISI of 250 ms, sometimes a forget cue appeared, indicating which items the participant was supposed to forget. Then, after a 3 second retention interval, a single recognition probe was presented in the center of the screen, and the participant indicated via a mouse button press whether or not that probe was included in the set of to-be-remembered words. Participants were instructed to respond as quickly and as accurately as possible. A 1500-ms ITI preceded the next trial.
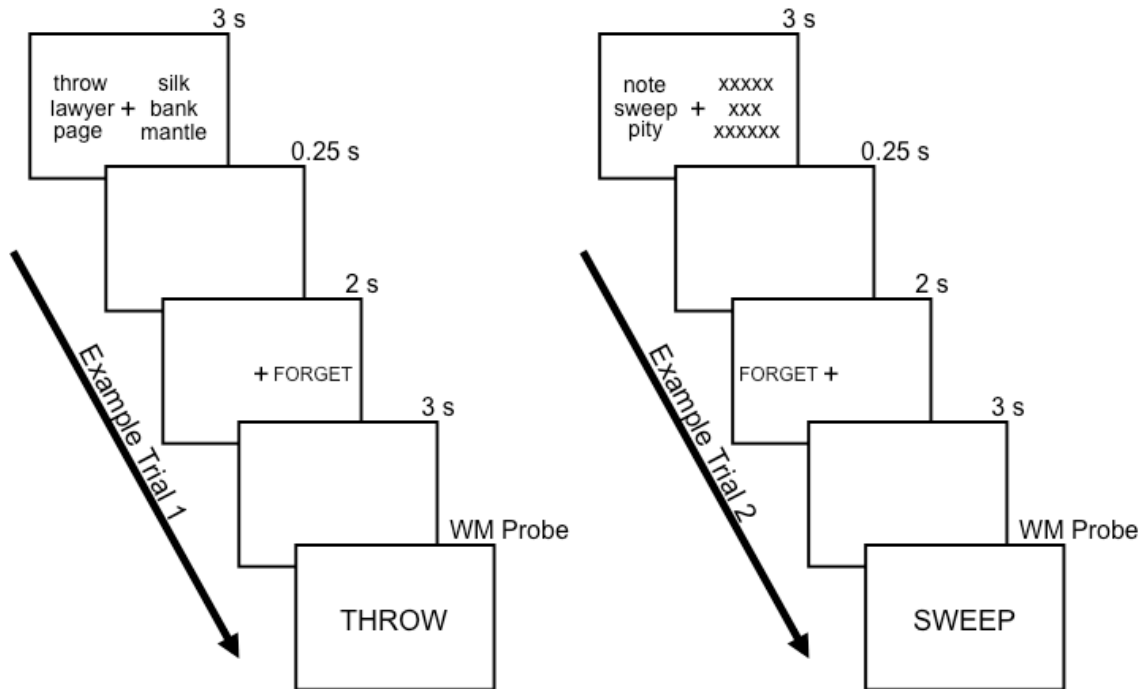
Figure 4.3 *Two sample working memory (WM) trials from Experiment 2. On Example Trial 1, "THROW" is a Remember-DF probe because it is one of the to-be-remembered items that was studied while simultaneously presented words were to-be-forgotten. On Example Trial 2, "SWEEP" is a Forget-3 probe because it was to-be-forgotten and no other competitors to remember were presented on that trial. (Note that Remember-3 trials were also included, so participants could never predict if they would need to forget or remember the stimuli.) After completing the entire working memory phase, participants completed a surprise long-term memory test. The critical long-term memory comparison, was between previously unprobed "Forget-DF" items (e.g., "BANK" in Example Trial 1) and previously unprobed "Forget-3" items (e.g., "NOTE" in Example Trial 2).*

The working memory trials were designed to optimize the number of the long-term memory trials of interest, while also preventing participants from being able to predict at encoding whether they would be asked to remember or forget particular items. On one third of the trials, two lists of words were presented on either side of the screen, and one side of the screen received a forget cue. These trials were the same as all of the trials in Experiment 1, and we label these trials as "DF" trials. DF trials could yield, "Forget-DF" probes and "Remember-DF" probes depending on whether a to-be-forgotten

or to-be-remembered word was probed at test. Further, "New-DF" probes were also possible if a new unstudied word was probed on a DF trial.

However, unlike in the first experiment, on one third of the trials, only one list of words was presented. On these trials, strings of XXXX's were presented on the other side of the screen. The strings of X's were of variable lengths, mimicking the variable lengths of real words. On these trials in which only 3 words were presented, half of the time a forget cue appeared, and participants needed to forget these three words—without having to simultaneously remember any other words (termed Forget-3 trials). On the other half of trials, a forget cue was not presented, and participants needed to remember all three words (termed Remember-3 trials). Finally, on the remaining third of trials, two lists of three words were presented. On half of these trials, a forget cue appeared on both sides of the screen and participants had to forget all six words (Forget-6 trials). On the other half of these trials, a forget cue did not appear, and participants had to remember all six words (Remember-6 trials). The order of these trials was randomized and was presented using EPrime software (Psychology Software Tools, Inc.).

The response rate for the working memory task was set at 1/3 affirmative responses and 2/3 negative responses to accommodate the greater incidence of trials where all words were forgotten. These trials (Forget-3 or Forget-6 trials) always required a negative response in the working memory phase because no to-be-remembered items were designated. For this reason, performance on these working memory trials is not informative. However, testing subsequent long-term memory of these words is critical to assess the efficiency of forgetting with and without competitors to remember. Nevertheless, on the working memory trials that always required a negative response

(Forget-3 & Forget-6), half of the probes were new words and half were members of the to-be-forgotten list. On trials in which all of the words were to-be-remembered, new probes were presented on half of the trials and to-be-remembered probes were presented on the other half of the trials. Finally, on normal directed forgetting trials (DF trials), half of the probes required an affirmative response, and the other half required a negative response.

After completing the WM trials, participants performed a surprise LTM recognition test. Performance on this test is of key importance for this experiment because it allows us to assess the critical question of whether forgetting was as efficient whether or not competitors to remember were simultaneously included. As in Experiment 1, during the long-term memory recognition test, participants viewed words presented one at a time and were asked to indicate whether or not they had studied the word before, regardless of its prior designation as to-be-forgotten or to-be-remembered. These LTM probes could be one of four different probe-types: Forget-3, Forget-DF, Remember-DF, or New. Only these probe-types were selected in order to maximize the number of probes from each critical condition. There were 48 LTM trials, and the probe rate was set to 50% negative and 50% affirmative responses. As such, there were 24 New probes, which required a "no" response, and 8 probes for each of the Forget-3, Forget-DF, and Remember-DF probes, all of which now required an affirmative response. In Experiment 2, the key comparison is between LTM performance for Forget-3 probes which had no competitors during encoding and Forget-DF probes which were encoded in the context of 3 to-be-remembered words.

The LTM probes were balanced as follows. Each probe word was originally presented equally often on the right or left of the screen and equally often in each of the three possible list positions. Further, for the Forget-DF and Remember-DF probes, half of the words were originally presented on trials that had received Remember probes in WM and the other half were presented on trials that had received negative probes. Of the trials that had previously received negative probes, half of these probes had been to-be-forgotten words and half had been new words. The Forget-3 probes originated from trials that had equally often received to-be-forgotten probes or new probes. As always, the LTM memory probes had never been previously probed in WM.

Results

Working Memory. Working memory performance was highly accurate (M = 0.95, SE = 0.01), indicating that participants were following task instructions. Although the most relevant results are evident in the long-term memory recognition test, we report working memory results that demonstrate typical directed forgetting effects. First, a paired t-test revealed that participants took significantly longer to correctly reject Forget-DF probes than to correctly reject New-DF probes, $t(35)$ = 5.21, $p < .001$, r = 0.66. Moreover, a Wilcoxon Signed Ranks test demonstrated that participants made significantly more false alarms to Forget-DF probes than to New-DF probes, z = 3.82, $p < .001$, r = 0.64. See Table 4.3 for descriptive statistics of response times and false alarm rates. Both results confirm the classic directed forgetting effects in working memory.

Table 4.3 *Mean response times (RTs) and false alarm rates in working memory for Forget-DF and New-DF probes as a function of articulatory suppression (AS) condition. Experiment 2 included the No AS condition, whereas Experiment 3 included the AS condition. Standard error is reported in parentheses.*

		Forget-DF	New-DF
RT	No AS	1082.23 (71.91)	862.24 (54.77)
	AS	1347.66 (70.01)	1048.56 (52.36)
False Alarms	No AS	0.19 (0.03)	0.03 (0.01)
	AS	0.42 (0.04)	0.08 (0.02)

Further, in working memory, we find evidence consistent with our load manipulations for to-be-remembered items. A Friedman's Test on positive probe accuracy revealed significant differences in accuracy between Remember-3, Remember-DF, and Remember-6 probes, $\chi^2(2) = 13.70$, $p = .001$. Follow-up Wilcoxon Signed Ranks tests demonstrated that participants were more accurate for Remember-3 probes than for Remember-DF probes, $z = 3.18$, $p = .001$, $r = 0.53$, and were more accurate for Remember-3 probes than for Remember-6 probes, $z = 2.92$, $p = .003$, $r = 0.49$. However, there were no significant differences in accuracy for Remember-DF and Remember-6 probes, $z = 1.46$, $p = .144$, $r = 0.24$. Thus, participants were more accurate on trials in which they were only required to encode three words. Providing further evidence of set-size effects, a repeated-measures ANOVA on RT indicated significant differences in RT for the Remember-3, Remember-DF, and Remember-6 probe conditions, $F(2, 70) = 13.84$, $p < .001$, $\eta_p^2 = 0.283$. Follow-up Bonferroni corrected pairwise comparisons revealed that participants correctly accepted Remember-3 probes and Remember-DF probes significantly faster than Remember-6 probes, $p < .001$ and $p = .007$, respectively.

But there were no significant differences in RTs for Remember-3 and Remember-DF probes, $p = .322$. Thus, participants took longer to respond when their memory set size was 6 items rather than 3 items. See Table 4.4 for descriptive statistics.

Table 4.4 *Mean working memory accuracy and response time (RT) as a function of probe-type and articulatory suppression (AS) condition. Experiment 2 included the No AS condition, and Experiment 3 included the AS condition. Standard error is reported in parentheses. Forget-DF and New probes required a "No" response, whereas Remember-3, Remember-DF, and Remember-6 probes required a "Yes" response. Note that New probes could appear on DF trials, Remember-3 trials, and Remember-6 trials. Accuracy for Forget-3 and Forget-6 trials are not reported in this table because, on these trials, participants always knew they should give a negative response before the probe word appeared.*

		Forget-DF	New	Remember-3	Remember-DF	Remember-6
Accuracy	No AS	0.81 (0.03)	0.97 (0.01)	0.97 (0.01)	0.89 (0.02)	0.84 (0.04)
	AS	0.57 (0.04)	0.96 (0.01)	0.87 (0.03)	0.71 (0.03)	0.75 (0.04)
RT	No AS	1082.23 (71.91)	854.50 (45.30)	764.75 (43.62)	800.63 (37.59)	907.58 (56.48)
	AS	1347.66 (70.01)	1038.08 (44.52)	1019.04 (54.55)	1102.16 (53.15)	1203.57 (76.44)

Long-term Memory. Assessment of long-term memory accuracy revealed the classic directed forgetting effect. Participants correctly recognized significantly more to-be-remembered words than to-be-forgotten words, $t(35) = 3.69$, $p = .001$, $r = 0.53$. Of crucial importance to the present experiment, however, we compared long-term memory accuracies for to-be-remembered items and to-be-forgotten items with and without competitors to remember. See Figure 4.4. Importantly, there were no significant differences in long-term memory accuracy for the Forget-3 and Forget-DF conditions,

$t(35) = 0.51$, $p = .617$, $r = 0.09$.[15] And, participants recognized significantly more to-be-remembered items than Forget-3 and Forget-DF items, $t(35) = 3.14$, $p = .003$, $r = 0.47$, $t(35) = 3.31$, $p = .002$, $r = 0.49$, respectively. Both of these DF effects were significantly different from zero, $t(35) = 3.14$, $p = .003$, $d = 0.52$, and $t(35) = 3.31$, $p = .002$, $d = 0.55$, for the Forget-3 and Forget-DF conditions, respectively. Thus, participants exhibited significant DF effects of similar magnitudes regardless of whether or not simultaneous remembering was required.
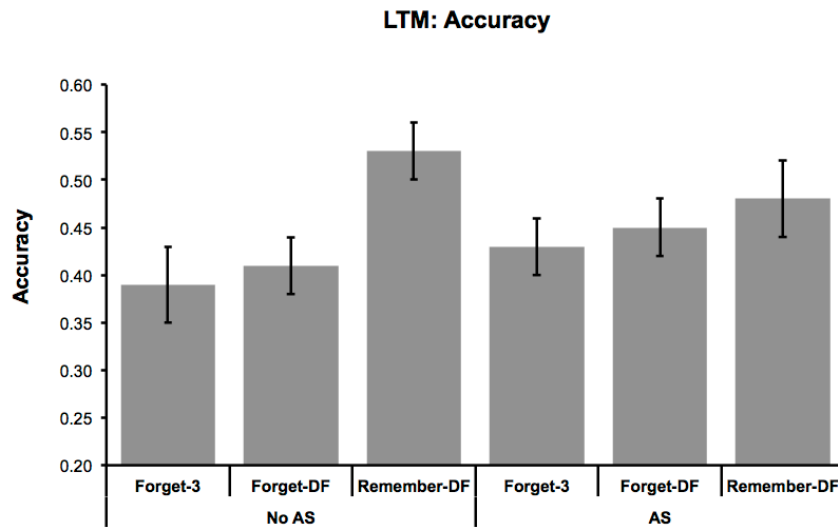
Figure 4.4 *Mean long-term memory accuracy (± standard error) for three different probe conditions. To-be-forgotten probes could have been either previously included on working memory trials with only 3 to-be-forgotten words (Forget-3) or on trials with 3 to-be-remembered and 3 to-be-forgotten words (Forget-DF). To-be-remembered probes were from trials that originally included 3 to-be-forgotten and 3 to-be-remembered words (Remember-DF). One group of participants did not perform articulatory suppression (No AS; Experiment 2). Another group preformed AS (Experiment 3). There was no significant difference in accuracy between the Forget-3 and Forget-DF conditions in either group. Further, AS interfered with the efficiency of implementing the forget instruction.*

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[15] A power analysis indicated that our design was capable of detecting a difference with an effect size of $f = 0.48$ or greater at a power of 0.80, and that a large sample of 1229 participants would be required to detect a significant difference (G*Power Version 3.1.9.2). The large sample that would be required to detect a difference of the size we observed is consistent with the minuscule effect size ($r = 0.09$) associated with this difference.

Discussion

Experiment 2 was designed to determine if selective rehearsal of to-be-remembered items was necessary for efficient forgetting. Results revealed similar long-term memory accuracy for to-be-forgotten probes regardless of whether or not participants needed to simultaneously remember additional items. Thus, these results indicate that selective rehearsal of to-be-remembered items was not necessary to perform directed forgetting within working memory, and that competitors to remember did not significantly assist nor hinder forgetting. Participants were capable of performing forgetting in isolation, without the requirement to simultaneously commit other to-be-remembered items to memory.

Experiment 3

By combining the prior experimental manipulations, in Experiment 3 we required participants to perform articulatory suppression during a directed forgetting task in which to-be-forgotten items were either presented in isolation or with simultaneous competitors to remember. This experiment will allow us to determine if articulatory suppression interferes with forgetting, even when simultaneously encoded to-be-remembered items are not present. Moreover, Experiment 3 will further assess the results found in the prior two experiments and will determine if similar patterns are found here. Results from Experiment 1 demonstrated that articulatory suppression interfered with directed forgetting, and results from Experiment 2 indicated that forgetting was as efficient whether or not participants had simultaneous competitors to remember. Based on these results, in Experiment 3, we predict that articulatory suppression will interfere with participants' ability to perform directed forgetting, and that, moreover, it will interfere

consistently with the Forget-3 and Forget-DF conditions. If forgetting operates similarly with and without the presence of competitors, articulatory suppression should exert similar effects on both conditions. This pattern of results would replicate and confirm the results from the prior two experiments, and would also establish that articulatory suppression can interfere with forgetting performed in isolation.

Method

      Participants. An additional thirty-six participants (23 women) volunteered to participate in this study. Participants ($M = 18.75$ years, $SE = 0.16$) received $10 or course credit for their participation and were treated within the ethical guidelines of the American Psychological Association. Prior to data analysis, fourteen additional participants were excluded for the following reasons: six participants reported only studying the first letter of the words, four participants reported not studying all of the words, two participants failed to respond on multiple trials, one participant reported a not attempting to forget any words, and one participant had working memory performance that fell below 2.5 standard deviations of the mean.

      Materials. The materials were identical to those used in Experiment 2.

      Procedure. The procedure was identical to that used in Experiment 2, with one key difference: In Experiment 3, participants were required to perform articulatory suppression as soon as the forget cue appeared and to continue performing articulatory suppression throughout the retention interval. The AS instructions were the same as those implemented in Experiment 1.

Results

In order to assess the effects of articulatory suppression on directed forgetting, we compared the data from Experiment 3 to that of Experiment 2. These statistical comparisons will reveal whether articulatory suppression interfered with directed forgetting, as well as whether or not participants were consistently able to forget targeted memoranda regardless of whether simultaneously presented to-be-remembered items were included.

Working Memory. On average, working memory performance was inferior with AS ($M = 0.88$, $SE = 0.01$) than without AS, $t(70) = 6.09$, $p < .001$, $r = 0.59$. To determine if all probe-types were equally impacted by AS, a 2 x 2 Mixed ANOVA was conducted comparing WM accuracy for New probes versus Old probes in the No AS and AS conditions. Old probes comprised all probe words that required a decision at test (Forget-DF, Remember-3, Remember-6, and Remember-DF). Forget-3 and Forget-6 probes were not included in this Old average because participants knew before the probe word appeared that they would have to reject that item. This ANOVA revealed a significant main effect of probe-type, such that participants were more accurate for New probes ($M = 0.97$, $SE = 0.01$) than for Old probes ($M = 0.80$, $SE = 0.01$), $F(1, 70) = 182.21$, $p < .001$, $\eta_p^2 = 0.722$, a significant main effect of AS, such that participants were less accurate with AS ($M = 0.84$, $SE = 0.01$) than without AS ($M = 0.93$, $SE = 0.01$), $F(1, 70) = 36.72$, $p < .001$, $\eta_p^2 = 0.344$, and a significant interaction between probe-type and AS, $F(1, 70) = 30.10$, $p < .001$, $\eta_p^2 = 0.301$. Follow-up independent samples t-tests on each of the probe-types individually indicated that this interaction occurred because there was no difference in accuracy for New probes with and without AS, $t(70) = 1.54$, $p = .128$, $r = 0.18$, but that

participants were more accurate without AS than with AS for Forget-DF probes, $t(70) =$ 4.77, $p < .001$, $r = 0.50$, for Remember-3 probes, $t(70) = 2.99$ $p = .004$, $r = 0.34$, for Remember-DF probes, $t(70) = 5.03$, $p < .001$, $r = 0.52$, and participants were marginally more accurate for Remember-6 probes without AS than with AS, $t(70) = 1.71$, $p = .092$, $r = 0.20$. See Table 4.4 for means and standard errors.

Next, we assessed the magnitude of the WM directed forgetting effects with and without AS. Evaluation of false alarms to Forget-DF probes and New-DF probes with and without AS in a 2 x 2 Mixed ANOVA revealed a significant main effect of probe-type, $F(1, 70) = 88.86$, $p < .001$, $\eta_p^2 = 0.559$, a significant main effect of AS, $F(1, 70) = 23.85$, $p < .001$, $\eta_p^2 = 0.254$, and a significant interaction, $F(1, 70) = 10.42$, $p = .002$, $\eta_p^2 = 0.130$. On average, participants made more false alarms to Forget-DF probes ($M = 0.31$, $SE = 0.03$) than New-DF probes ($M = 0.06$, $SE = 0.01$), and made more false alarms with AS ($M = 0.25$, $SE = 0.02$) than without it ($M = 0.11$, $SE = 0.02$). Yet, the significant interaction occurred because participants exhibited differentially more false alarms to Forget-DF probes than New-DF probes with AS. Independent samples t-tests confirmed that participants made significantly more false alarms to Forget-DF probes with AS than without AS, $t(70) = 4.77$, $p < .001$, $r = 0.50$, but there was no significant difference in false alarms to New-DF probes with and without AS, $t(70) = 1.54$, $p = .128$, $r = 0.18$. Thus, AS interfered with directed forgetting and resulted in false endorsement of to-be-forgotten words as members of the to-be-remembered list at a rate that exceeded the rate of additional false alarms to New-DF probes with AS. See Table 4.3.

Another 2 x 2 Mixed ANOVA was conducted on RT as a function of probe-type (Forget-DF or New-DF) and AS (No AS or AS). This analysis indicated that participants

took significantly longer to reject Forget-DF probes ($M = 1214.95$, $SE = 50.18$) than New-DF probes ($M = 955.40$, $SE = 37.89$), $F(1, 70) = 60.28$, $p < .001$, $\eta_p^2 = 0.463$, and took longer to respond with AS ($M = 1198.11$, $SE = 56.12$) than without AS ($M = 972.24$, $SE = 60.33$), $F(1, 70) = 7.52$, $p = .008$, $\eta_p^2 = 0.097$. However, the interaction between probe-type and AS condition did not reach significance, $F(1, 70) = 1.40$, $p = .241$ $\eta_p^2 = 0.020$. Thus, the selective adverse effect of AS on accuracy for Forget-DF probes was not also reflected in RT. Instead, participants consistently took longer to reject Forget-DF probes than New-DF probes, and adding AS similarly extended these RTs.

Finally, we assessed the influence of AS on our load manipulations of to-be-remembered items. A 3 x 2 Mixed ANOVA was run on WM accuracy as a function of probe-type (Remember-3, Remember-DF, and Remember-6) and AS (No AS or AS). There was a significant main effect of probe-type, $F(2, 140) = 13.14$, $p < .001$, $\eta_p^2 = 0.158$, as well as a significant main effect of AS, $F(1, 70) = 19.95$, $p < .001$, $\eta_p^2 = 0.222$, such that participants were more accurate without AS ($M = 0.90$, $SE = 0.02$) than with AS ($M = 0.78$, $SE = 0.02$). However, the interaction did not reach significance, $F(2, 140) = 1.74$, $p = .180$, $\eta_p^2 = 0.024$. Follow-up Bonferroni corrected pairwise comparisons on the main effect of probe-type indicated that participants were significantly more accurate for Remember-3 probes compared to Remember-DF probes and Remember-6 probes, both $ps < .001$. However, there was no difference in accuracy for Remember-6 and Remember-DF probes, $p = 1$.

Another 3 x 2 Mixed ANOVA was run on WM RT as a function of to-be-remembered load and AS. Results indicated a significant main effect of probe-type, $F(2, 140) = 12.17$, $p < .001$, $\eta_p^2 = 0.148$, and a significant main effect of AS, $F(1, 70) = 17.74$,

$p < .001$, $\eta_p^2 = 0.202$, but no significant interaction, $F(2, 140) = 0.30$, $p = .745$, $\eta_p^2 =$ 0.004. The significant main effect of AS occurred because people took longer to respond to to-be-remembered probes when they had to perform AS ($M = 1108.26$, $SE = 51.41$) than when they did not ($M = 824.32$, $SE = 43.62$). Follow-up pairwise comparisons on the main effect of probe-type indicated that participants took longer to respond to Remember-6 probes than Remember-3 probes and Remember-DF probes, $p < .001$ and $p = .009$, respectively. However, there was no difference in RT for Remember-3 and Remember-DF probes, $p = .133$.

Long-term Memory. A 2 x 2 Mixed ANOVA was conducted to compare long-term memory accuracy for to-be-remembered and to-be-forgotten items with and without AS. Results revealed the classic directed forgetting effect, such that participants had better memory for to-be-remembered items ($M = 0.51$, $SE = 0.02$) than for to-be-forgotten items ($M = 0.42$, $SE = 0.02$), $F(1, 70) = 12.95$, $p = .001$, $\eta_p^2 = 0.156$. There was no significant main effect of AS, $F(1, 70) = 0.04$, $p = .840$, $\eta_p^2 = 0.001$. Importantly, the two-way interaction approached significance, $F(1, 70) = 3.28$, $p = .074$, $\eta_p^2 = 0.045$. This marginal interaction occurred because accuracy for to-be-remembered items decreased with AS, whereas accuracy for to-be-forgotten items increased with AS. Without AS there was a significant difference in accuracy between to-be-remembered and to-be-forgotten items (see Experiment 2), but with AS there was no longer a significant difference in accuracy between to-be-forgotten and to-be-remembered items, $t(35) = 1.32$, $p = .197$, $r = 0.22$. Thus, like Experiment 1, these results confirm that AS interfered with directed forgetting. Note also that there was no significant difference in long-term memory accuracy for New probes with and without AS, $t(70) = 0.78$, $p = .438$, $r = 0.09$,

indicating that articulatory suppression differentially impacted memory for to-be-forgotten and to-be-remembered items.

An additional analysis was performed to compare the magnitude of the directed forgetting effect with and without AS for conditions in which forgetting was performed in isolation (Forget-3) or in which forgetting and simultaneous remembering were required (Forget-DF). Critically, there was no significant difference in the magnitude of the directed forgetting effect for the Forget-3 ($M = 0.08$, $SE = 0.03$) and Forget-DF ($M = 0.10$, $SE = 0.03$) conditions, $F(1, 70) = 0.99$, $p = .323$, $\eta_p^2 = 0.014$.[16] Thus, participants consistently performed directed forgetting as efficiently regardless of whether simultaneous remembering was required. There was also a marginal main effect of AS, such that participants had larger DF effects without AS ($M = 0.14$, $SE = 0.04$) than with AS ($M = 0.04$, $SE = 0.03$), $F(1, 70) = 3.28$, $p = .074$, $\eta_p^2 = 0.045$, consistent with the conclusion that articulatory suppression interferes with forgetting. Further, no significant interaction was present between the Forget-3 and Forget-DF conditions and the AS conditions, $F(1, 70) = 0.02$, $p = .889$, $\eta_p^2 = 0.000$, indicating that the similar DF effect magnitude for Forget-3 and Forget-DF probes held true regardless of the AS condition. Finally, one-sample t-tests comparing DF effect magnitudes to zero indicated that with AS there were no significant DF effects for either the Forget-3 or the Forget-DF conditions, $t(35) = 1.51$, $p = .141$, $d = 0.25$, and $t(35) = 0.91$, $p = .369$, $d = 0.15$, which contrasts with the significant DF effects present without AS (see Experiment 2).

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[16] We are confident that this null effect is reliable. A power analysis indicated that our design was capable of detecting differences with effects sizes of $f = 0.14$ or greater at a power of 0.80 (G*Power Version 3.1.9.2).

Discussion

In Experiment 3, participants were required to perform articulatory suppression while completing a working memory directed forgetting task in which forgetting was occasionally performed in isolation or with additional competitors to remember. Results from Experiment 3 replicated the findings from the prior two experiments: Articulatory suppression interfered with directed forgetting efficiency, and it interfered consistently regardless of whether or not participants needed to rehearse to-be-remembered items concurrently. Thus, these results indicate that articulatory suppression interfered with forgetting even when simultaneous remembering was not required. We also note that articulatory suppression significantly interfered with remembering within working memory, which is consistent with the typical effects of disrupting sub-vocal rehearsal (e.g., Larsen & Baddeley, 2003). This reduction in memory for to-be-remembered items likely contributed to the reduced efficiency of directed forgetting and the diminished long-term DF effect, although, importantly, articulatory suppression also interfered with forgetting when to-be-remembered competitors were absent. Implications of these findings and the findings of the prior two experiments are considered in the General Discussion.

General Discussion

Results from the present experiments begin to address the mechanisms underlying directed forgetting in working memory. Experiment 1 tested the influence of articulatory suppression on directed forgetting efficiency; Experiment 2 tested whether selective rehearsal of to-be-remembered items was needed to perform directed forgetting in working memory; and Experiment 3 combined the manipulations from the prior two

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experiments and assessed the influence of articulatory suppression on forgetting when simultaneous remembering was not required. Results consistently showed that directed forgetting within working memory is an active control process that was interfered with by articulatory suppression, and that selective rehearsal of to-be-remembered items is not necessary for efficient forgetting. Although many questions remain pertaining to the exact manner in which directed forgetting is implemented in working memory, these experiments lay the foundation for further experimental work to continue to elucidate this question. Below, we elaborate upon how our findings relate to prior studies of directed forgetting, and we discuss several additional mechanistic questions that remain unanswered.

Experiments 1 and 3 included an articulatory suppression manipulation aimed to disrupt sub-vocal rehearsal and to introduce a secondary task that would require processing resources to perform. We posited that if directed forgetting in working memory relied on selective rehearsal of to-be-remembered items or if it was an active control process, then articulatory suppression may interfere with directed forgetting by disrupting rehearsal and taxing the executive resources needed to efficiently forget. Alternatively, we posited that articulatory suppression might assist with rehearsal termination of to-be-forgotten items by preventing any inadvertent rehearsal of these items, thus facilitating forgetting. Results consistently indicated that articulatory suppression interfered with directed forgetting, evidenced by increased false alarms to to-be-forgotten probes in working memory and diminished long-term directed forgetting effects with articulatory suppression (see also Shebilske et al., 1971, who used math subtraction problems as distractors in a different directed forgetting paradigm). Thus,

these findings suggest that directed forgetting in working memory relies on selective rehearsal of to-be-remembered memoranda and/or requires executive processing resources that articulatory suppression limited. Moreover, importantly, these results indicate that disrupting sub-vocal rehearsal with articulatory suppression did not assist with forgetting. Although this result indicates that directed forgetting in working memory does not operate via the passive rehearsal cessation of to-be-forgotten items, we note that *active* rehearsal cessation is still a possible alternative—people may use executive resources to implement the termination of rehearsal of to-be-forgotten items (cf. Fawcett & Taylor, 2012). In other words, articulatory suppression may have interfered with a resource-demanding decision to stop rehearsal of specific to-be-forgotten memoranda or with a resource-demanding execution of this goal.

To determine if efficient forgetting relied on differential rehearsal of to-be-remembered items, Experiments 2 and 3 manipulated whether forgetting was performed in isolation, or if participants had to concurrently forget and concurrently remember different stimuli. We evaluated the efficiency of these two instances of forgetting by assessing the long-term memorability of this information. Three different outcomes were possible, each implicating a different mechanism. If selective rehearsal of to-be-remembered items was necessary to perform directed forgetting within working memory, then participants would exhibit better long-term memory accuracy (i.e., worse forgetting) for to-be-forgotten items processed without concurrent remembering. Alternatively, if the inclusion of concurrent to-be-remembered items interfered with directed forgetting, then participants would exhibit worse long-term memory accuracy (i.e., better forgetting) for to-be-forgotten items processed in isolation. In essence, simultaneously presenting to-be-

remembered items might have been akin to requiring dual-task performance and may have consequently disrupted participants from solely executing the forget instruction. Finally, if selective rehearsal of to-be-remembered items was not necessary and if the inclusion of to-be-remembered items was not disruptive, then forgetting would be as efficient regardless of whether simultaneous remembering was required. Two independent participant groups repeatedly showed similar long-term memory performance for to-be-forgotten items that were forgotten in isolation and for to-be-forgotten items that were forgotten with simultaneously encoded competitors to remember. Thus, these findings suggest that selective rehearsal of to-be-remembered items is not necessary to perform directed forgetting in working memory. Moreover, the results indicate that the requirement to commit additional items to memory does not significantly interfere with one's ability to execute the forgetting. Finally, articulatory suppression interfered with forgetting even when simultaneous rehearsal of to-be-remembered items was not possible, suggesting that an active control process is involved even when to-be-remembered items are not present.

Relationship to Other Proposed Directed Forgetting Mechanisms

Although limited work has been conducted to test the mechanisms of directed forgetting performed during working memory, we review some of the proposed mechanisms of directed forgetting within long-term memory, as these mechanisms may similarly apply. Classically, a dissociation has been identified between the mechanisms underlying item-method and list-method long-term directed forgetting. In item-method directed forgetting each stimulus is presented one-at-a-time, followed by a cue that indicates whether or not the prior stimulus was to-be-remembered or to-be-forgotten,

whereas in list-method directed forgetting, participants are often told to forget the previously learned list of stimuli and are presented with a new list to remember (see MacLeod, 1998). Based on the differences in the experimental protocols and the differences in the observed effects following these instructions, item-method directed forgetting tends to be associated with selective rehearsal (e.g., Basden et al., 1993; Bjork, 1972; MacLeod, 1975; Woodward et al., 1974), whereas list-method directed forgetting tends to be associated with retrieval inhibition (e.g., Basden et al., 1993; Bjork, 1989; Geiselman & Bagheri, 1985; Geiselman, Bjork, & Fishman, 1983; MacLeod, 1998) and contextual change accounts (e.g., Pastötter & Bäuml, 2007; Sahakyan & Kelley, 2002). Indeed, these list-method accounts are largely driven by the staggered and separate processing of to-be-forgotten and to-be-remembered information. Given that our working memory paradigm requires the concurrent encoding of to-be-forgotten and to-be-remembered memoranda, we believe that the effects observed in our paradigm are less influenced by the proposed list-method mechanisms. Instead, some of the item-method accounts seem more applicable, such as selective rehearsal (e.g., Basden et al., 1993; Bjork, 1972), active withdrawal of processing resources (e.g., Fawcett & Taylor, 2008), and set segregation (e.g., Bjork, 1970). Active *item inhibition* of to-be-forgotten items shortly after encoding could also contribute to the effects we observe (cf., Anderson & Green, 2001; Fawcett & Taylor, 2008, 2012; Zacks & Hasher, 1994). However, a *retrieval inhibition* account is less likely because we find long-term directed forgetting effects with tests of recognition memory, whereas list-method paradigms that typically favor retrieval inhibition fail to observe directed forgetting effects when memory is

probed with recognition tests (e.g., Geiselman & Bagheri, 1985; Geiselman, Bjork, & Fishman, 1983; MacLeod, 1998).

According to the selective rehearsal account, participants preferentially rehearse to-be-remembered items over to-be-forgotten items (e.g., MacLeod, 1975). Note, however, that although this mechanism is more suited to the item-method design, Sheard and MacLeod (2005) suggest that selective rehearsal can still operate during list-method directed forgetting if sufficient opportunity for selective rehearsal of the lists is provided (see also Bjork, 1970). The existing theoretical definition of selective rehearsal implies that it requires both differential rehearsal of to-be-remembered items and rehearsal cessation of to-be-forgotten items. But, the item-method paradigm does not allow for the isolation of these two processes. Aside from a potential forget cue presented on the first trial, in the item-method it is impossible for participants to perform forgetting without also having the opportunity to remember other information. Participants can always rehearse prior to-be-remembered items. Our working memory directed forgetting paradigm, however, does not have this issue, as to-be-remembered words are relevant on only one trial. In Experiments 2 and 3, we included some trials in which participants needed to forget all of the words and no simultaneous remembering was required. Thus, we were able to specifically test whether selective rehearsal of to-be-remembered items was necessary to perform directed forgetting within working memory. Critically, our research demonstrated that directed forgetting in working memory did not require the selective rehearsal of to-be-remembered items to be effective. Thus, it follows that directed forgetting in working memory operates by a different underlying mechanism such as active rehearsal cessation of to-be-forgotten items (cf. Fawcett & Taylor, 2012),

active inhibition of to-be-forgotten items (cf. Ludowig et al., 2010; Wylie, Foxe, &

Taylor, 2008), or active set differentiation (cf. Bjork, 1970, 1972).

Our finding that directed forgetting is an active control process is consistent with

a number of previous item-method studies. For instance, Fawcett and Taylor (2008)

required participants to complete a secondary probe detection task after receiving the

instruction to remember or forget the previous item. They found that participants took

longer to detect the secondary probes at short stimulus onset asynchronies after an item

received a forget instruction compared to after an item received a remember instruction.

The authors interpret these results to indicate that participants were engaging an active

control process following the forget instruction that impaired their secondary probe

detection ability. Notably, this active mechanism was further supported in several follow-

up experiments from the same group (Fawcett & Taylor, 2010, 2012). Moreover, in

another item-method experiment Ludowig et al. (2010) measured intracranial event-

related potentials (ERPs) in response to forget or remember cues. Hippocampal negative

ERPs were of diminished magnitudes following to-be-forgotten cues that elicited

successful subsequent forgetting, similarly leading the authors to favor an active

suppression mechanism of this form of directed forgetting. Zacks, Radvansky, and

Hasher (1996) also support an active inhibition hypothesis because they found that older

adults, who are thought to execute worse inhibition, exhibited poorer directed forgetting

than younger adults. Furthermore, Wylie, Foxe, and Taylor (2008) conducted an item-

method directed forgetting task using functional magnetic resonance imaging (fMRI).

Their results similarly endorsed an active control process, as unique frontal regions

including the superior frontal gyrus and medial frontal gyrus displayed greater activity

during intentional forgetting when compared to unintentional forgetting and intentional remembering, respectively (see also Rizio & Dennis, 2013). Our data similarly implicate an active control process at play within working memory. Thus, the active mechanisms proposed to underlie item-method directed forgetting may similarly be involved in directed forgetting within working memory.

Another proposed mechanism of directed forgetting within long-term memory involves set differentiation (e.g., Bjork, 1970, 1972; Horton & Petruk, 1980; Shebilske et al., 1971). Participants must be able to efficiently designate which items are members of the to-be-remembered set and which items are members of the to-be-forgotten set. If they make errors in this set differentiation, they will not be able to implement the forget cue efficiently (i.e., they may try to remember some of the items that they were supposed to forget and vice versa). Because identifying which set of words received a forget instruction is also of critical importance in our working memory paradigm, we postulate that a similar set differentiation mechanism may be involved. For instance, in Experiments 1 and 3, articulatory suppression may have interfered with a set differentiation process, contributing to more false alarms to to-be-forgotten probes and less efficient long-term forgetting. Thus, we assert that set differentiation is also a viable candidate mechanism that may contribute to directed forgetting within working memory. Note, however, that this mechanism would not have a role in the Forget-3 condition. Thus, while set differentiation may contribute to directed forgetting in some contexts, it is not an obligatory process for directed forgetting success.

Future Directions

Although these experiments begin to address the mechanisms of directed forgetting in working memory, questions still remain. Future studies can be designed to further illuminate how people control the contents of working memory. For instance, future studies could be conducted to examine whether directed forgetting reduces the memory representations below a baseline level in an active suppression manner similar to that supported in the Think/No-Think paradigm (e.g., Anderson & Green, 2001; Anderson et al., 2004). As such, in addition to the to-be-remembered and to-be-forgotten conditions, an extra encode-only condition could be included. Long-term memorability of to-be-remembered and to-be-forgotten items could be compared to this alternative baseline condition to determine if remembering boosts memory strength and forgetting decreases memory strength. Moreover, indirect tests of memory could also be implemented to assess the relative availability of these memory representations. For instance, a word-stem completion task or a lexical decision task could be used to ascertain the implicit accessibility of the previously encoded, remembered, or forgotten items. In a similar vein, solution words from the remote associates test (RAT) could be given either to-be-remembered or to-be-forgotten instructions within our working memory task. If participants were later asked to complete these RAT problems, they might complete fewer problems that had to-be-forgotten solutions, if forgetting decreased the availability of these items in memory.

Another lingering question pertains to the specificity of the observed articulatory suppression effects. Was there something special about articulatory suppression that interfered with forgetting, or would any secondary task interfere in a similar manner

simply by taxing executive resources? Future experiments can be designed to address this question by testing other intervening tasks to determine if any secondary task will interfere with directed forgetting within working memory, or if targeting the verbal articulatory loop exerts unique effects.

Moreover, although our experiments consistently establish that the long-term fate of the to-be-forgotten items is consistent regardless of whether simultaneous remembering is required, they do not provide an index of the short-term efficiency of this forgetting. Future experiments could be conducted to assess the effectiveness of forgetting with and without simultaneous remembering within working memory. For instance, we have previously demonstrated that directed forgetting reduces proactive interference and semantic interference within working memory (Festini & Reuter-Lorenz, 2013, 2014). Additional experiments could be run to determine if the reduction in proactive interference or semantic interference in working memory was consistent regardless of whether or not simultaneous remembering was required. This type of experiment may require the use of a greater number of working memory trials in order to achieve sufficient frequencies of critical trial types. Increasing the working memory trial number would preclude the possibility of including an additional long-term memory assessment as we did here, since unpublished pilot work in our lab has documented the reduced sensitivity of long-term recognition tests with greater numbers of working memory trials and the resulting larger corpus of stimuli.

Additionally, it is possible that requiring a probe decision on DF trials but not requiring a probe decision on Forget-3 trials influenced the execution of forgetting. An additional experiment could be conceived that sometimes does not probe either DF or

Forget-3 trials. The efficiency of forgetting in both of these unprobed conditions could be compared. Moreover, the design of the competitors experiment did not allow for the determination of whether to-be-remembered items were remembered better in isolation in long-term memory, and an additional experiment could be run to test this question.

Finally, the applicability of directed forgetting instructions to real world situations warrants careful study. Determining if people are able to perform directed forgetting to focus on important information within everyday environments will be informative. For instance, research could be conducted to establish if directed forgetting can be implemented in educational contexts. Additional research could discern if directed forgetting could be a tool to boost memory for populations that typically show impoverished memory (i.e., older adults) or for stimuli that are particularly difficult to remember (i.e., proper names). Expanding our understanding of how people implement directed forgetting will assist in determining what environmental applications are appropriate.

Conclusions

This set of experiments began to address the mechanisms of directed forgetting in working memory. Specifically, we evaluated the influence of articulatory suppression on directed forgetting effectiveness, as well as whether selective rehearsal of to-be-remembered items was necessary for efficient directed forgetting in working memory. Results consistently demonstrated that articulatory suppression did not assist, but rather interfered with both short- and long-term effects of directed forgetting. Moreover, our experiments indicated that directed forgetting does not require selective rehearsal of to-be-remembered items to be implemented, as participants had similar long-term memory

for to-be-forgotten items that were forgotten either with or without concurrently processed to-be-remembered items. In combination, these data suggest that directed forgetting within working memory involves an active control process, one that can operate without the requirement to focus attentional and memorial processes on to-be-remembered items. Although more research needs to be done to pinpoint the underlying mechanisms of directed forgetting in working memory, this research establishes several important results, allowing for further methodological and theoretical investigation.

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Chapter 5: Conclusion

This dissertation examined the memorial outcomes of performing directed forgetting within working memory and also tested several candidate mechanisms of its operation. The overarching goal was to (1) test how effectively directed forgetting was implemented in working memory, and to (2) assess the role of rehearsal in this type of memory control. In sum, the results demonstrated (a) that directed forgetting could be performed efficiently within working memory, leading to reductions in both semantic and proactive interference and diminished long-term memory, (b) that forgetting could be implemented without simultaneous rehearsal of to-be-remembered items, and (c) that directed forgetting required executive control processes that were interfered with by articulatory suppression. The experimental evidence supporting these conclusions is briefly summarized below.

First, I documented the effectiveness of directed forgetting within working memory by probing both implicit measures of memorial interference and explicit long-term memorability of this information. The experiments in Chapter 2 demonstrated that directed forgetting decreased semantic interference in working memory and reduced false memory errors in both working memory and long-term memory (Festini & Reuter-Lorenz, 2013). Furthermore, the experiments in Chapter 3 established that directed forgetting similarly reduced recency-induced proactive interference (Festini & Reuter-Lorenz, 2014). Moreover, both chapters revealed that performing directed forgetting within working memory also decreased veridical long-term memory of to-be-forgotten

information compared to to-be-remembered information. In combination, these findings suggest that directed forgetting within working memory attenuates the strength of the memory representations of to-be-forgotten items and that directed forgetting can operate efficiently in working memory.

Next, the experiments in Chapter 4 began to address *how* people perform directed forgetting within working memory. Results from these experiments indicated that people were capable of forgetting targeted information even without the presence of competitors to remember; selective rehearsal of to-be-remembered items was not necessary to perform directed forgetting successfully within working memory. Moreover, articulatory suppression interfered with directed forgetting efficacy even when to-be-remembered competitors were absent, implicating an active control process that requires executive support. Thus, together, these experiments better characterize how directed forgetting is performed during working memory, expanding our understanding of this form of motivated forgetting.

Limitations

Before proceeding to discuss the implications of this body of work, several limitations of our experimental paradigm warrant consideration. First, the present experiments solely examined directed forgetting in working memory with emotionally neutral information, therefore the extent to which they would generalize to emotionally salient words is unknown (cf. Joormann, Nee, Berman, Jonides, & Gotlib, 2010; Berman et al., 2011; see also, Joormann, 2010). Further, the present experiments solely included forget cues. Questions still remain regarding whether remember cues or other importance cues lead to similar effects as forget cues. Finally, unlike some other methods used for

motivated forgetting (e.g., the Think/No-Think paradigm, extinction of conditioned fear), the current directed forgetting paradigm did not target and repeatedly test the forgetting of specific memories.

Future Directions

Although the present research begins to characterize the effectiveness and execution of directed forgetting within working memory, additional research should be conducted to address lingering questions. For instance, as has been discussed in detail in Chapter 4, questions remain pertaining to *how* people implement directed forgetting in working memory. Set differentiation and inhibitory mechanisms should be examined to determine if and how these processes contribute to this type of cognitive control. For example, by modulating the distinctiveness of to-be-remembered and to-be-forgotten items (i.e., by manipulating font similarity) we could test how set differentiation may influence directed forgetting within working memory. Further, to test an inhibitory account, the accessibility of to-be-forgotten items could be compared to that of control items that were encoded but not dealt with further (i.e., by administering a lexical decision task or the Remote Associates Test).

Testing the specificity of the articulatory suppression effects on directed forgetting is also crucial for our understanding of the type of executive resources needed to implement directed forgetting in working memory efficiently. To address this question I am currently investigating whether a secondary manual finger tapping task impairs directed forgetting in a similar manner as articulatory suppression. These results will help reveal if characteristics unique to the articulatory suppression manipulation are driving the observed effects.

The present research also only focused on performing directed forgetting within working memory. Although some experiments assessed the long-term memory outcomes of this directed forgetting method, additional assessment of directed forgetting performed during long-term memory itself was not conducted. Future research could directly compare directed forgetting within working memory to that in canonical long-term memory item-method and list-method paradigms to determine if directed forgetting within working memory affords more targeted control. Evaluating the magnitudes of the directed forgetting effects elicited in all situations, while controlling for the total number of to-be-forgotten and to-be-remembered memoranda, would help answer this question. Additional assessment of the incidence of false memories for to-be-forgotten information following these different directed forgetting techniques would provide another index of efficiency. It would be informative to run variations of these paradigms with identical stimuli to enable concrete comparisons between the methods, as these working memory and long-term memory directed forgetting comparisons are currently lacking.

Finally, collecting neuroimaging data using the working memory directed forgetting paradigm would help answer neuromechanistic questions. For instance, contrasting forgetting in the presence and absence of to-be-remembered competitors would help determine if the underlying neural mechanisms in these two conditions are similar or distinct. Moreover, assessing task-locked differences in the Blood-Oxygen-Level Dependent (BOLD) signal for subsequent successful and unsuccessful forgetting during working memory and long-term memory tests would help reveal the neural circuits responsible for efficient forgetting. Additionally, functional connectivity analyses could be conducted to determine if perhaps prefrontal seed regions exhibit stronger

functional connectivity with the hippocampus and medial temporal lobe during successful remembering and if weaker functional connectivity is present between these regions during successful forgetting. Conducting these additional experiments would help create a more detailed account of the cognitive, behavioral, and neural properties and mechanisms of directed forgetting within working memory.

Potential Real World Applications

Inspecting both the effectiveness and the mechanisms of implementing directed forgetting in working memory within a controlled laboratory setting was critical in beginning to understand this control process. Nevertheless, it is important to conduct applied research that examines whether directed forgetting can similarly be exercised in real world scenarios. A first step would be to include affective information in the current working memory paradigm. Moreover, testing whether importance or value cues influence memorial processes in a similar manner as directed forgetting cues will help determine if directed forgetting can be effectively extended to everyday situations. If value cues lead to similar effects as directed forgetting cues, then it may be beneficial to explicitly assign high values to everyday information that warrants accurate memory (i.e., by highlighting particularly important information in the classroom or by giving bonuses for recalling specific targeted information). Assessing the efficiency of directed forgetting in applied scenarios will help to establish whether the beneficial effects of directed forgetting within working memory that we observe under highly controlled laboratory settings (i.e., the decreases in memorial interference, false memories, and long-term memory) yield similar performance benefits in everyday life situations.

Theoretical Implications

In addition to answering specific questions about the properties of directed forgetting in working memory, these experiments are also germane to several larger theoretical frameworks. Each chapter discussed many of these relevancies in depth. Below, I reconsider several important theoretical implications and pose several additional implications.

False Memory Theories. By assessing the influence of directed forgetting on the susceptibility to false memory errors, the experiments in Chapter 2 informed theories of false memory formation. First, the results confirmed that false memories and semantic interference were evident several seconds after the study episode and were not confined to long-term memory (Atkins & Reuter-Lorenz, 2008, 2011; Coane, McBride, Raulerson, & Jordan, 2007). Further, the finding that directed forgetting reduced semantic effects for to-be-forgotten items was consistent with the *fuzzy trace theory* (Reyna & Brainerd, 1995) and with *global-matching models* (e.g., Arndt & Hirshman, 1998), as forgetting may have reduced both verbatim and gist memory traces and may have also diminished the sum signal of familiarity of to-be-forgotten items. Importantly, the present data demonstrated that an *implicit associative response* (e.g., Collins & Loftus, 1975; Roediger, McDermott, & Robinson, 1998; Underwood, 1965) at *encoding* was not sufficient to produce strong false memories for to-be-forgotten items, as being instructed to forget targeted information *after* encoding lead to decreases in false memories and semantic interference. Directed forgetting during working memory succeeded at reducing semantic memory errors, indicating that the forgetting decreased the memorial signals that promote memory distortions.

Working Memory and Long-term Memory Continuity. By testing the efficiency of directed forgetting performed during working memory after both short and long delays, the present experiments also inform theories of working memory and long-term memory continuity. Whereas some research finds support for distinct memorial processes in working memory and long-term memory, other research favors common memorial operations (for a summary see Jonides et al., 2008). The fact that directed forgetting reduced false recognition in both working memory and long-term memory lends support for the presence of similar memorial processes in both instances. This finding is consistent with the documented similarities in short- and long-term false memories in the absence of directed forgetting (Flegal, Atkins, & Reuter-Lorenz, 2010).

Moreover, our finding that controlling the contents of working memory influenced long-term memory for this information is compatible with research that finds a role of the dorsolateral prefrontal cortex (DLPFC) in long-term memory formation (e.g., Blumenfeld & Ranganath, 2006; Ranganath, Cohen, & Brozinsky, 2005), as the DLPFC has been shown to be involved in working memory and executive control (e.g., see Levy & Goldman-Rakic, 2000; Yuan & Raz, 2014). Further, these similar short- and long-term memorial effects following directed forgetting within working memory are also compatible with research that finds a role of the hippocampus and medial temporal lobes in both working memory and long-term memory (e.g., Nee & Jonides, 2011; Ranganath et al., 2005; Schon, Ross, Hasselmo, & Stern, 2012). Thus, the present data support the continuity of memorial processes in working memory and long-term memory, and we would predict involvement of both prefrontal and medial temporal regions in our task. Nevertheless, although the present research implicates that some memorial processes

similarly operate in both memory domains, this does not necessitate complete overlap between all short- and long-term memorial processes.

Models of Cognitive Load. The present research is also applicable to models of cognitive load in working memory. According to the *time-based resource-sharing model* (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007), cognitive load increases as a function of attention-capturing executive control operations. In a series of experiments, Barrouillet et al. (2007) demonstrated that individuals exhibited inferior working memory spans when secondary tasks required (a) longer retrieval times from long-term memory, (b) more difficult response selection, (c) both long-term memory retrieval and response selection as opposed to sole response selection, and (d) choice response selection compared to simple response execution. All of these results supported their model of cognitive load: working memory load increases and working memory performance decreases when attention-capturing executive control prevents the refreshing of working memory representations. Our finding that articulatory suppression, an attention-demanding secondary task, interfered with working memory performance is consistent with their model. Future research could also utilize our working memory directed forgetting paradigm and additional parametrically-varied Remember-All control conditions to further test this model by examining how directed forgetting may decrease cognitive load by reducing the number of working memory representations that must be maintained and how it may increase cognitive load by requiring the implementation of attention-demanding executive operations.

Levels of Processing. Finally, the current directed forgetting work could be interpreted according to a levels of processing account (e.g., Craik & Lockhart, 1972;

Craik & Tulving, 1975). It has been repeatedly demonstrated that people have better memory for information that they process deeply (i.e., relate to themselves, make into sentences) compared to information that they process shallowly (i.e., focus on the surface features, rehearse rotely). Thus, one interpretation of the diminished memory for to-be-forgotten items could adopt a levels of processing explanation: people may have inferior memory for to-be-forgotten items because they process these items shallowly whereas they process to-be-remembered items deeply. Deep processing during working memory has been shown to boost long-term memorability of that information (Flegal & Reuter-Lorenz, 2014). Yet, levels of processing manipulations have been shown to have little effect on working memory performance (Flegal & Reuter-Lorenz, 2014, Exp. 1; Rose, Myerson, Roediger, & Hale, 2010), or they even have the opposite effect (Flegal & Reuter-Lorenz, 2014, Exp. 2, in which shallow processing increased false memories in short-term memory). Thus, because directed forgetting lead to short-term reductions in semantic interference, proactive interference, and false memories within working memory, a mechanism other than shallow processing is likely at play.

Final Remarks

Not all memories are of equal priority. Consequently, researchers have addressed possible manners in which people can control the contents of their memory (e.g., Anderson & Green, 2001; Banich, Mackiewicz, Depue, Whitmer, Miller, & Heller, 2009; Basden, Basden, & Gargano, 1993). Directed forgetting is one method of memory control that has received considerable attention, but the majority of research on directed forgetting has focused on controlling long-term memory representations (see MacLeod, 1998). This dissertation extended the work on directed forgetting within working

memory, empirically testing the short- and long-term memorial consequences of performing this type of forgetting. A key feature of this form of memory control is that it operates on a small number of currently active working memory representations, thus potentially promoting more targeted cognitive control. Although more research is required to fully understand the manner in which this type of cognitive control is executed, these experiments provide a foundation upon which additional research can be built. Importantly, this dissertation reveals that memory control via directed forgetting within working memory can operate in isolation without simultaneous remembering, requires executive resources to implement, and elicits reduced memorial effects that are evident after seconds and that persist across time.

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