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

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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.

Keywords: directed forgetting, false memory, working memory, long-term memory

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

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 paper 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.[i] 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 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; Narine, 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.[ii] 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 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.[iii]

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 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.

Experiment 1

Method

Participants. Thirty-five individuals (28 women) volunteered to participate in this study.[iv] 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 directed forgetting cue was also presented (see Figure 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 1 about here.)

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 1 and Table 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.[v]

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-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.

(Table 1 about here.)

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 (Nee et al., 2007; Oberauer, 2001).

(Table 2 about here.)

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.

Experiment 2

Method

Participants. Fifty-six individuals (37 women) volunteered to participate in this study.[vi] 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 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.[vii] See Table 1 and Table 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.

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 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)[viii], 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.[ix]

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-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, 1998). 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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Table 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 (0.02)	0.06 (0.01)	0.03 (0.02)	0.09 (0.03)
2	WM	0.02 (0.01)	0.04 (0.01)	0.01 (0.00)	0.07 (0.01)
	LTM	0.24 (0.02)	-	0.13 (0.02)	0.30 (0.03)

Table 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)

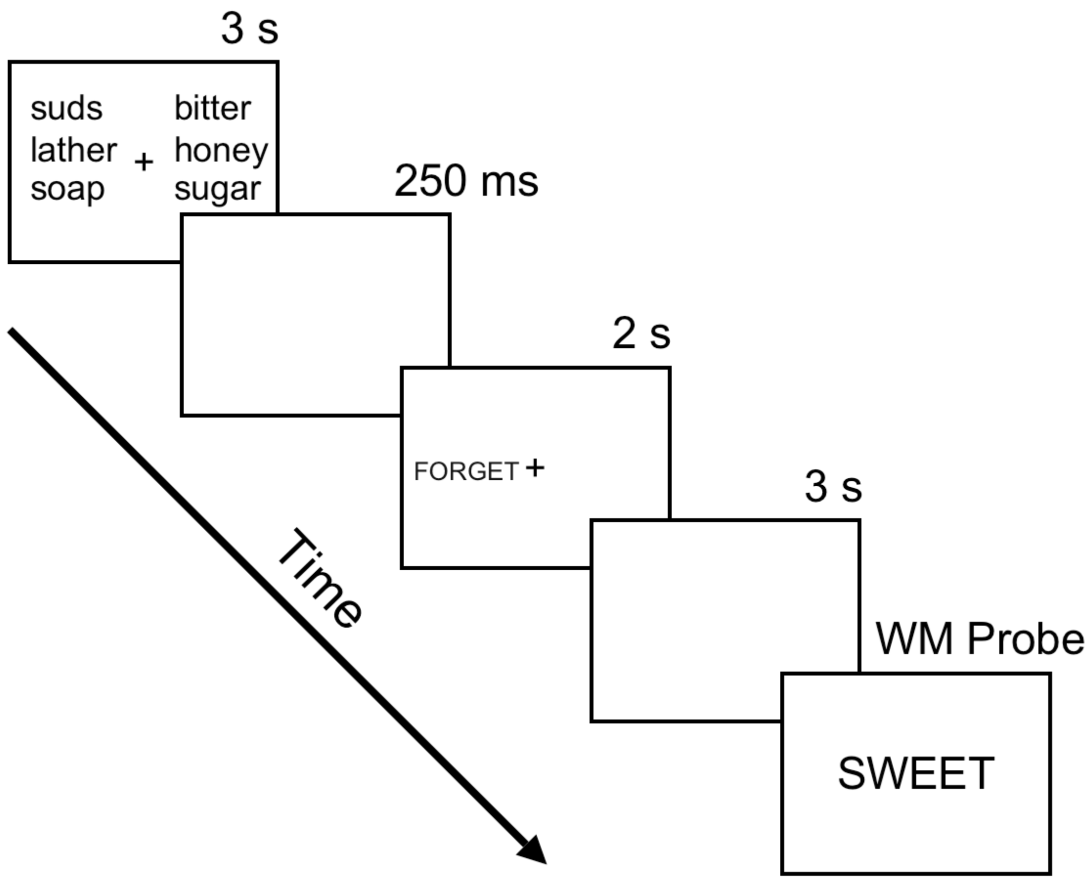

Figure 1. Diagram of the false memory directed forgetting task as implemented in Experiment 1. In this example, the probe word "SWEET" is a Remember-Related probe. In Experiment 2, after the entire working memory phase, participants completed a surprise long-term memory test.

Footnotes

[i] 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.

[ii] 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.

[iii] 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.

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

[v] 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.

[vi] 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.

[vii] 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.

[viii] 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.

[ix] 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.