

## Forgetting as an Active Process: An fMRI Investigation of Item-Method-Directed Forgetting

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**Using event-related functional magnetic resonance imaging (fMRI), we examined the blood oxygen level-dependent response associated with intentional remembering and forgetting. In an item-method directed forgetting paradigm, participants were presented with words, one at a time, each of which was followed after a brief delay by an instruction to Remember or Forget. Behavioral data revealed a directed forgetting effect: greater recognition of to-be-remembered than to-be-forgotten words. We used this behavioral recognition data to sort the fMRI data into 4 conditions based on the combination of memory instruction and behavioral outcome. When contrasted with unintentional forgetting, intentional forgetting was associated with increased activity in hippocampus (Brodmann area [BA] 35) and superior frontal gyrus (BA10/11); when contrasted with intentional remembering, intentional forgetting was associated with activity in medial frontal gyrus (BA10), middle temporal gyrus (BA21), parahippocampal gyrus (BA34 and 35), and cingulate gyrus (BA31). Thus, intentional forgetting depends on neural structures distinct from those involved in unintentional forgetting and intentional remembering. These results challenge the standard selective rehearsal account of item-method directed forgetting and suggest that frontal control processes may be critical for directed forgetting.**

**Keywords:** attention, control, directed forgetting, fMRI, memory

### Introduction

In many cognitive models of memory, forgetting is treated as a failure to encode, maintain, or retrieve information; it has been hypothesized to result from various processes including passive decay, interference, interrupted consolidation, and retrieval failure (see Neath and Surprenant 2003 for a review). Indeed, in our day-to-day activities, we often lament forgetting as evidence for a lapse in memory, and countless websites attest to the widespread desire to improve memory either through the application of behavioral techniques or medical intervention. Whether memory complaints involve mild slips or clinically significant memory impairment, a common theme is that forgetting represents a failure to intentionally commit information to memory and/or to retrieve that information when needed.

This contrasts sharply with intentional forgetting. Rather than treating forgetting as a memory failure, Bjork (1989) has emphasized its adaptive function when information becomes outdated or irrelevant. Indeed, even though forgetting is frequently cited as a source of human error (e.g., Reason 1995, 2005; Hobbs and Williamson 2003; Krulak 2004), success in the workplace often derives from employees' ability to relinquish outdated technologies in favor of emerging ones (e.g., Sterns and Dorsett 1994) and to adapt to workplace changes (e.g., Yeatts et al. 2000).

Clearly, in day-to-day activities, adaptive functioning is best served by preventing outdated or irrelevant information from interfering with current processing and recollections. Relative deficits in the ability to intentionally forget information have been implicated in age-related declines in memory function (Zacks et al. 1996; Andrés et al. 2004; although see Gamboz and Russo 2002) and in some patient groups (e.g., obsessive-compulsive disorder: Wilhelm et al. 1996; Tolin et al. 2002; temporal lobe epilepsy: Fleck et al. 1999). Thus, to the extent that intentional forgetting is a desirable and adaptive outcome, it can be distinguished from unintentional forgetting. Whereas unintentional forgetting can be characterized as a failure to remember, intentional forgetting would seem to be a strategic memorial function that helps reduce interference in the processing and/or retrieval of relevant information.

The strategic mechanism that subserves successful intentional forgetting depends on whether or not the item has been encoded into long-term memory by the time the instruction to forget is received. On the one hand, if an item has already been committed to long-term memory, then its existing representation cannot be readily expunged. Instead, the forget instruction likely causes the representation of that item to be suppressed or inhibited such that upon subsequent retrieval attempts, its reactivation is less probable than other representations that have not been suppressed or inhibited. Such is thought to occur when a list-method directed forgetting paradigm is used (e.g., Geiselman et al. 1983; Bjork 1989; Basden et al. 1993; although see Sahakyan and Kelley 2002) or when a think/no-think paradigm is used (e.g., Anderson and Green 2001; Anderson 2003; Anderson et al. 2004). On the other hand, if an item has not already been committed to long-term memory, then the instruction to forget can prevent this commitment. In this case, forgetting does not operate on a stored representation; instead, it operates on the processes that would otherwise lead to long-term storage. In this case, forgetting may occur through the passive decay of a working memory trace (i.e., by simply "dropping" the item from the rehearsal set) or through its active suppression (Zacks et al. 1996). Whether passive or active, this sort of forgetting occurs by preventing long-term memory formation; it may occur for a list of items designated as to-be-forgotten, or even for a single item (e.g., Gottlob et al. 2006). Such is thought to be the case when an item-method directed forgetting paradigm is used (e.g., Basden et al. 1993; MacLeod 1999).

In the item-method directed forgetting paradigm—which is the paradigm of interest for the present investigation—words are presented one at a time. After a delay (~2–3 s), participants receive an instruction to either remember (R) or forget (F)

the word. Thus, participants are aware that instructions will be received on a trial-by-trial basis and that each word has an equal chance of being associated with an R or an F instruction. Rather than engage in elaborative rehearsal of items that are as likely to be followed by an F instruction as an R instruction, participants are thought to use maintenance rehearsal to hold the word in working memory until the presentation of the memory instruction. If an R instruction is received, participants engage in elaborative rehearsal; if an F instruction is received, participants eliminate the word from their rehearsal set. Consistent with the view that directed forgetting in this paradigm is accomplished by mechanisms engaged at encoding, poorer memory performance for F items relative to R items is observed on tests of both recall and recognition (e.g., Basden et al. 1993; MacLeod 1999; see also Basden BH and Basden DR 1998).

Although a selective rehearsal account can accommodate poorer recall and recognition of F than R items, it is not clear how selection is achieved. The common notion seems to be that the F instruction causes maintenance rehearsal to cease and the F word decays passively in the absence of elaborative encoding effort. Alternatively, forgetting may involve an active process that engages attentional/executive control mechanisms. Zacks et al. (1996) argued that the receipt of an F instruction causes attention to be withdrawn from F items and inhibited from returning to their representations. Because this view suggests that identity and semantic priming from F word primes should be relatively slower than from R word primes, the failure to observe this pattern of results has been used to argue against attentional inhibition of F words at encoding (Marks and Dulaney 2001). Other evidence, however, suggests that attention may, in fact, be withdrawn from the spatial representation of peripherally presented F words (Taylor 2005). Moreover, in a study that combined an item-method paradigm with a stop-signal paradigm, Hourihan and Taylor (2006) argued that forgetting might be analogous to preventing the commission of a prepotent overt response (see also Anderson 2003). In essence, an F instruction engages a stop process that actively competes with the go process associated with committing a word to memory. When the stop process successfully outruns the go process (cf. Logan and Cowen 1984; Logan 1994), the end result may be weak or nonexistent encoding of the F item.

To the extent that executive control over overt behavior is associated with activity in frontal areas (e.g., Pliszka et al. 2000; Overtoom et al. 2002; Aron et al. 2003; Rieger et al. 2003), one might expect frontal involvement in item-method directed forgetting as well. Consistent with this suggestion, Paz-Caballero et al. (2004) examined event-related potentials (ERPs) at the time of memory instruction and identified differences that distinguished high and low magnitudes of behavioral directed forgetting. Following an F instruction, they observed early frontal and prefrontal activity that may have served to limit parietal activity otherwise associated with maintaining the item representation. When Ullsperger et al. (2000) examined ERPs at recognition, they observed qualitatively different patterns of old/new effects for R and F items with F items showing less early activity at midfrontal sites, greater late activity at right-frontal sites, and an absence of activity at parietal sites (Ullsperger et al. 2000). Notably, these qualitative differences in scalp topography for R and F old/new effects were not replicated by a level of processing manipulation.

Differential frontal and parietal activity has also been implicated in a functional magnetic resonance imaging (fMRI)

examinations of activation during the study phase of an item-method directed forgetting task. By distinguishing memory instruction from behavioral outcome, Reber et al. (2002) separated encoding effort from encoding success. In a region of interest (ROI) in the left inferior prefrontal cortex (LIPFC), they observed that an R instruction produced a greater percent signal change over time than an F instruction, regardless of behavioral outcome. In an ROI in the left medial temporal lobe (MTL), they observed a greater percent signal change for words that were later remembered compared with words that were later forgotten, regardless of instruction. Based on these findings, Reber et al. (2002) argued that the LIPFC (i.e., frontal regions) might modulate processing in temporal regions (MTL) related to memory encoding.

Whereas, Reber et al. (2002) were interested in differentiating encoding effort and encoding success during the study phase, the present study used fMRI results during study to examine proposed mechanisms of intentional forgetting in the item-method paradigm. In the study phase, words were presented one at a time, followed by an R or F instruction (as explained above). In the test phase, all words were re-presented randomly mixed with an equal number of new (foil) words and participants were asked to categorize each word as old or new, regardless of the R/F instruction that had been presented at study. Behavioral performance on the recognition test was used post hoc to sort scanning epochs taken during study (see also Reber et al. 2002). Conditions were distinguished according to the combination of memory instruction (R, F) and behavioral outcome (Remember, making correct “old” response to R and F words; Forget, making incorrect “new” responses to R and F words). This resulted in 4 instruction-outcome conditions: R-Remember, R-Forget, F-Remember, F-Forget. Under the assumption that participants intended to comply with the task instructions (e.g., MacLeod 1999), R-Remember and F-Forget were taken as measures of intentional remembering and intentional forgetting, respectively. By the same reasoning, F-Remember and R-Forget were taken as measures of unintentional (incidental) remembering and unintentional (accidental) forgetting, respectively.

### *Is Forgetting an Active Cognitive Process?*

If forgetting is a passive process, an instruction to forget—regardless of outcome—should primarily manifest as a failure to engage cognitive processes needed to commit an item to memory. However, if intentional forgetting is an active process, one might expect a distinct pattern of activation associated with F instructions relative to that associated with R instructions. This pattern should emerge in areas known to be involved in episodic encoding (e.g., MTL, frontal areas; Davachi et al. 2001; Davachi and Wagner 2002) and/or in those known to be involved in the suppression of unwanted responses (e.g., Aron et al. 2003; Aron and Poldrack 2006).

The view that intentional forgetting is an active cognitive process also predicts an interaction of memory intention and behavioral outcome. Consider that, under normal circumstances, the perirhinal cortex shows increased activity during the encoding of words that are subsequently recognized versus not recognized (Davachi et al. 2003). A converse comparison reveals greater activity in posterior cingulate, bilateral inferior parietal, and medial parietal/precuneus cortices during encoding of words that are later not recognized versus recognized

(Wagner and Davachi 2001). If intentional forgetting proves to be distinguishable from unintentional forgetting in our paradigm, then activations at encoding should reveal that the processes leading to forgetting following an F instruction are distinguishable from processes leading to forgetting following an R instruction. These differences may occur within the same regions that are involved in unintentional forgetting (see above) and/or in other areas, such as frontal regions implicated in executive control (e.g., inferior frontal gyrus; cf. Aron et al. 2003).

Of course, unique activations only indicate that intentional forgetting is distinguishable from unintentional forgetting and intentional remembering at the neural level. This differentiation may occur because intentional forgetting is an active cognitive process, as suggested by Zacks et al. (1996). Or it may occur because intentional forgetting engages areas in common with unintentional forgetting and intentional remembering, but on a different time course (e.g., with a longer decay function compared with unintentional forgetting) and/or with different magnitudes of activation/deactivation.

### Is Intentional Forgetting Achieved by Active Suppression?

To provide support for active suppression during intentional forgetting, it is necessary to demonstrate not only that intentional forgetting is distinguishable from unintentional forgetting and from intentional remembering but also that intentional forgetting engages networks known to be involved in cognitive control. To the extent that intentional forgetting involves control networks engaged during task-switching (e.g., Dreher and Berman 2002; Brass and von Cramon 2004; Wylie et al. 2004, 2006) and motor response inhibition (e.g., Pliszka et al. 2000; Overtoom et al. 2002; Aron et al. 2003; Rieger et al. 2003), unique activations associated with intentional forgetting should occur within frontal areas, particularly the inferior frontal cortex (e.g., Aron et al. 2003; Aron and Poldrack 2006).

## Methods

### Participants

Participants were eleven young ( $M = 26$ , standard deviations [SD] = 6.0), neurologically normal, right-handed individuals (6 females). All had normal color vision and sufficiently good acuity to discriminate the stimuli without glasses at the distance used. All provided written informed consent, the procedures of which were approved by the Institutional Review Board of the Nathan S. Kline Institute for Psychiatric Research. The data from one participant were not included in the

analyses because of anomalously high false alarm rates on the recognition test (more than 4 SD higher than the average of the remaining participants).

### Apparatus

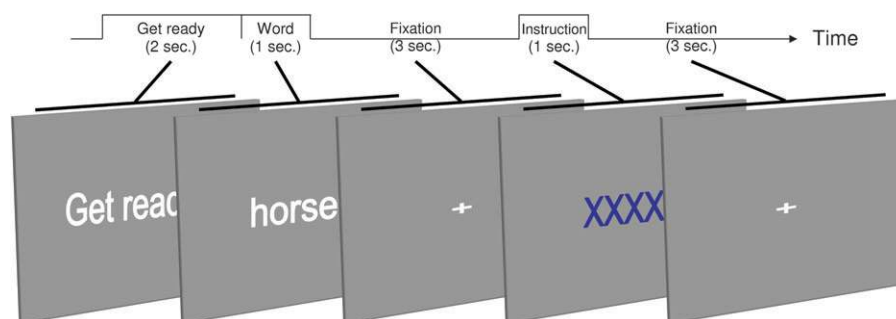
A Siemens 1.5T VISION magnet was used for both the functional and anatomical data collection. Stimuli were delivered using an Integrated Functional Imaging System-Stand Alone stimulus-delivery system (MRI Devices Corp., Waukesha, WI), which is equipped with a 640 × 480 LCD panel that was mounted on the head coil, directly in the participants' line of vision. Head motion was minimized using the standard Siemens head holder.

The Presentation software package (Version 0.80, www.neurobs.com) was used to present stimuli and to collect responses. This was run on a Dell Optiplex GX 240 desktop that was interfaced with the IFIS system. Responses were collected using an magnetic resonance (MR)-compatible, 2-button response pad (Lumina LP-400 response pad system; Cedrus, www.cedrus.com). All participants responded with the index and middle fingers of the right hand.

### Stimuli

A 200-word list was created using the Paivio Word List Generator (<http://www.math.yorku.ca/SCS/Online/paivio/>) and is shown in Appendix A. The following are mean descriptive statistics for this generated list: Kucera-Francis word frequency, 34.15 (SD = 12.08,  $R = 20-50$ ); imagery rating, 5.35 (SD = 5.35,  $R = 2.0-6.9$ ); concreteness rating, 5.38 (SD = 1.66,  $R = 2.0-7.0$ ); meaningfulness, 6.19 (SD = 0.889,  $R = 3.72-8.16$ ); number of syllables, 1.99 (SD = 0.86,  $R = 1.0-5.0$ ); and number of letters, 6.36 (SD = 2.04,  $R = 3.0-12.0$ ). For each participant, 2 lists of 54 words each were created by drawing randomly without replacement from this list of 200 words. One list was presented during the study phase; the other was used as foil items during recognition. Of the words used in the study phase, each word was randomly assigned to one of two subsets: an R subset and an F subset. During the study phase, each trial began with the prompt "Get ready" (2 s), followed by the presentation of 1 of the 54 words (1 s). Three seconds later, a memory instruction was presented for 1 s that informed participants whether to remember or forget the word. This memory instruction was a string of 5 uppercase Xs that were colored either blue or yellow and presented in the center of the computer monitor. Half of the participants were instructed to commit words followed by blue Xs to memory and to forget words followed by yellow Xs; the other half received the reverse designation. Each trial ended with a period of rest that lasted for 3 s. Thus, each trial lasted 10 s (5 repetition times [TRs], see below). A graphical depiction of this sequence is shown in Figure 1. Because of limitations in the number of acquisitions that the MR scanner could make in a single session, the study phase was divided into 2 blocks of 27 trials each.

The recognition phase followed immediately after the end of the study phase, allowing for time to start the recognition trial sequence (~5 min). In the recognition phase of the experiment, R and F study words were presented, intermingled with an equal number of foils. Each trial of this phase began with the presentation of a word for 1 s and participants were instructed to press one button if the word had been presented during the study phase (old)—*regardless* of the previous instruction about whether to remember it or not—and another button if the



**Figure 1.** A graphical depiction of the sequence of events in a single trial of the encoding block.

word had not been presented previously (new). The importance of disregarding the previous R or F memory instruction was stressed. After each word was presented, 4 s elapsed before the next prompt to get ready was presented. Participants were allowed to respond at any point during this interval. Thus, each trial during this phase lasted 5 s.

### Procedure

Scanning occurred during study as well as during recognition; the recognition data will be reported elsewhere. Prior to entering the scanner, all participants were instructed about the basic structure of the experiment. They were told that on each trial, a word would be presented in the center of the screen and that after a brief interval they would receive an instruction to remember or forget that word. It was also explained that a recognition memory test would follow. The fact that they would be asked to attempt to recognize all of the words seen in the study phase was carefully withheld.

At the beginning of both study blocks, the instructions were presented on the screen. These included the mapping of the colored Xs (yellow, blue) to the appropriate memory instruction (R, F). At the beginning of the recognition phase, the relevant instructions were presented on the screen and the requirement to respond to any previously encountered words, regardless of whether they had been followed by an R or F instruction, was stressed.

Following scanning, all participants were debriefed and were asked whether they had attempted to recognize all the words from the study phase (regardless of memory instruction). All participants reported having done so.

### fMRI Data Collection

The hemodynamic response evoked by the tasks was inferred from single-shot, T2\* weighted, echo planar imaging sequences on the Siemens 1.5T magnet. Images were acquired with a TR of 2 s, an echo time (TE) of 50 ms, and a 90° flip angle. Each of the volumes consisted of 22 slices (voxel size = {3.91 × 3.91 × 5 mm}); matrix size = {64 × 64 voxels}, which allowed for whole-brain coverage. During each of the study blocks, 140 volumes were acquired. Although the data are not reported here, 277 volumes were acquired during the recognition block. Prior to data analysis, the first 5 volumes of each block were discarded to account for the time needed for the field to achieve a steady state. Onset of the volume acquisitions was triggered by a Transistor-Transistor Logic pulse generated by the Presentation stimulus delivery software (www.neurobs.com). Thus, time ( $T = 0$ ) is precisely defined for both the Siemens volume acquisitions and the beginning of stimulus delivery.

### Anatomy

High-resolution whole-brain images were acquired using the same Siemens 1.5T magnet with a 3D T1-weighted magnetization-prepared rapid gradient echo sequence. A total of 202 anatomical slices were acquired (voxel size = 1 mm<sup>3</sup>; matrix size = {256 × 256}; TR = 11.6 ms; TE = 4.9 ms; flip angle = 8°) for coregistration with the fMRI data.

### fMRI Data Analyses

All images were realigned using Analysis of Functional NeuroImages (AFNI) (Cox 1996), and any blocks in which the participant moved more than one voxel in any dimension or more than a degree in pitch, roll, or yaw were discarded. Each raw time series of signal strength for each participant was first time-shifted so that the slices were “aligned” temporally (i.e., shifted so that the slices have the same temporal origin) and any linear trends in the data were removed. All of the volumes in the time series were then spatially registered using an image midway through the time series as canonical. All voxels outside the brain were eliminated from further analysis. The hemodynamic response was modeled by a delayed gamma function, and this function was coded into the design matrix as a regressor. This has been shown to be a robust method of estimating the hemodynamic response when the precise timing of the onset of the rise of the hemodynamic response is not known (Ollinger et al. 2001). Contrasts were specified using the General Linear Model, using a corrected voxel-level probability threshold of 0.05. The correction for multiple comparisons was achieved by including a cluster-level threshold of 18 contiguous voxels that was determined

using the AlphaSim program (available at <http://afni.nimh.nih.gov>), with Monte Carlo simulations restricted to the gray matter. Where we had prior hypotheses, based on previous studies, we interrogated a spherical volume (radius = 10 mm) centered on the location previously reported. For this small volume, a cluster of only 3 contiguous voxels was sufficient to correct for multiple comparisons.

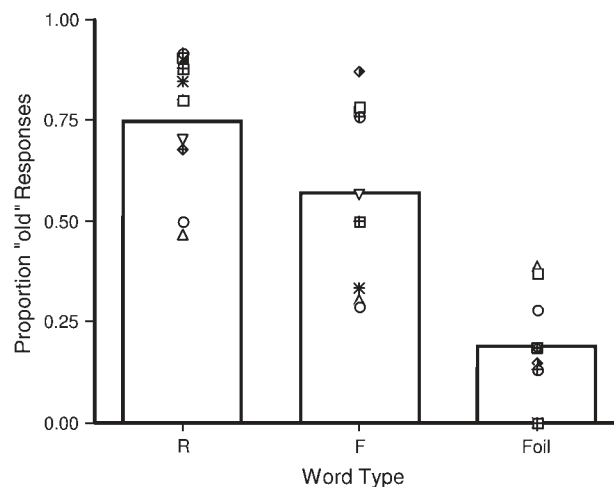
## Results

### Behavioral Data

The mean proportion of old responses made on the recognition test are shown in Figure 2 as a function of word type (R, F, Foil); these data represent hits for R and F words and false alarms for Foil words. A within-subjects analysis of variance (ANOVA) on these data revealed a significant main effect of word type,  $F_{2,18} = 29.94$ , mean squared error = 0.027,  $P < 0.01$ . Planned contrasts revealed a significant directed forgetting effect, wherein participants had fewer recognition hits to F than to R words,  $F_{1,18} = 6.02$ ,  $P < 0.03$ . Even so, the proportion of “old” responses made to F words was significantly greater than the proportion of such responses made to Foil words,  $F_{1,18} = 26.31$ ,  $P < 0.01$ . This latter finding argues that the near-chance hit rate for F words (0.57) does not reflect random responding, although participants recognized fewer F than R words they did, in fact, recognize a significant number of F words.

### fMRI Data

Scans acquired during the study phase were sorted post hoc based on hits/misses made during the recognition of R and F words. (Sorting the data in this way meant that, for some participants, there were relatively few trials in each cell of the design matrix. To assess the power of the effects reported here, we calculated the effect size (Cohen’s  $d$ ) for our results. The effect sizes ranged from 2.18 to greater than 5. That is, even the smallest effect size in these data was very robust (a “large” effect size is  $d \geq 0.8$ .) This allowed us to determine how activations revealed during the study were related to the intention to remember or forget and to the success in instantiating those intentions. These data are summarized in Table 1.



**Figure 2.** Proportion old responses on the recognition test, as a function of word type (R, F, Foil). Bars depict average group data; lines depict individual performance for each of the 10 participants.

**Table 1**  
Encoding activations to survive correction for multiple comparisons

	BA	X	Y	Z	Volume
<b>Main effects</b>					
F-instructions > R-instructions					
Superior medial, frontal gyrus	BA10	-6	67	12	6574
Middle frontal gyrus	BA6	-34	27	60	1835
Middle cingulate gyrus	BA31	18	-33	40	2293
Middle/superior temporal gyrus	BA39	58	-65	24	5198
Middle temporal gyrus	BA21	66	-17	-8	3134
Parahippocampal gyrus	BA34	-14	-5	-20	5580
Parahippocampal gyrus	BA35	18	-25	-20	3669
R-instructions > F-instructions					
Middle frontal gyrus	BA9	-26	35	16	192
Insula	BA13	30	7	16	512
Forgotten > Remembered					
Inferior frontal gyrus	BA47	42	23	-8	1987
Putamen		-26	-1	4	1605
Remembered > Forgotten					
Inferior frontal gyrus	BA45	-58	15	0	192
Inferior parietal lobule	BA40	-34	-37	32	1605
Parahippocampal gyrus	BA30	-26	-53	12	1758
Parahippocampal gyrus/hippocampus	BA36	-26	-33	0	640
Parahippocampal gyrus	BA19	34	-53	0	1529
Lingual gyrus/cerebellum (declive)	BA18	6	-69	-24	2752
<b>Interaction</b>					
Instruction × outcome					
Inferior frontal gyrus	BA47	50	19	-8	1835
Insula/inferior frontal gyrus	BA13	46	3	16	1987
Inferior parietal lobule	BA40	-38	-29	28	1605
Thalamus/pulvinar		-6	-21	12	1911
Inferior frontal gyrus	BA45	-54	35	0	1452
Parahippocampal gyrus	BA36	-34	-33	-20	2675
Superior frontal gyrus	BA10	-30	59	28	1376
Inferior temporal gyrus	BA20	54	-21	-20	1682
Postcentral Gyrus	BA1/3	-54	-17	52	2446
<b>Contrasts</b>					
R-Remember > R-Forget					
Middle frontal gyrus	BA46	-54	35	32	1835
Inferior parietal lobule	BA40	-34	-37	32	1987
Cingulate gyrus	BA32	26	15	24	2675
Parahippocampal gyrus	BA30	-10	-29	44	2370
Perirhinal cortex	BA20	-36	-10	-22	192
Middle occipital gyrus	BA18	-26	-89	4	2905
Caudate body		-14	-13	24	1529
Precuneus/caudate tail		-26	-49	16	2370
Thalamus/pulvinar		-2	-25	8	2370
Cerebellum/declive		-34	-77	-28	2523
F-Forget > F-Remember					
Superior/middle frontal gyrus	BA10	-30	55	24	1452
Inferior frontal gyrus	BA47	46	23	-8	6650
Postcentral gyrus	BA4	54	-13	32	1758
Putamen		-26	-1	4	1835
R-Remember > F-Remember					
Superior frontal gyrus	BA9	-34	35	32	2140
Postcentral gyrus	BA3	-46	-13	56	1376
F-Forget > R-Forget					
Superior frontal gyrus	BA10/11	18	63	-12	2599
Inferior/middle frontal gyrus	BA9	26	15	28	1376
Inferior parietal lobule	BA40	-58	-57	48	2599
Parahippocampal gyrus/hippocampus	BA35	22	-17	-12	4204
Posterior cingulate	BA31	22	-29	40	320

Note: Activations are given in Talairach coordinates (x, y, z) and volume is in mm<sup>3</sup>. Areas in italics are replications of previous findings.

The data were analyzed using a 3-factor ANOVA (3dANOVA3, part of the AFNI suite of image analysis programs). The factors were Memory Instruction (R vs. F), Outcome (Remember vs. Forget) and Subject, which was a random factor. In addition to the main effects and interaction, 4 planned contrasts were included: R-Remember-R-Forget; F-Forget-F-Remember; R-Remember-F-Remember; and F-Forget-R-Forget.

### Memory Instruction

Here, we examined the difference in activation on R instruction and F instruction trials. Whereas greater activity for R than F

trials was found in middle frontal gyrus and insula (see also Reber et al. 2002), we found greater activity for F than R trials in frontal and medial temporal areas (see Fig. 3). As shown in Table 1, these areas included activations in middle frontal gyrus, middle cingulate gyrus, middle temporal gyrus, and parahippocampal gyrus. If intentional forgetting were achieved simply by passive decay (i.e., the obverse of intentional remembering), this comparison would have revealed few, if any, unique activations. The fact that there were unique activations—and in areas involved in memory formation (see Buckner et al. 1999)—supports the view that active cognitive processes are engaged by an F instruction; intentional forgetting is not simply a failure to intentionally remember.

### Memory Outcome

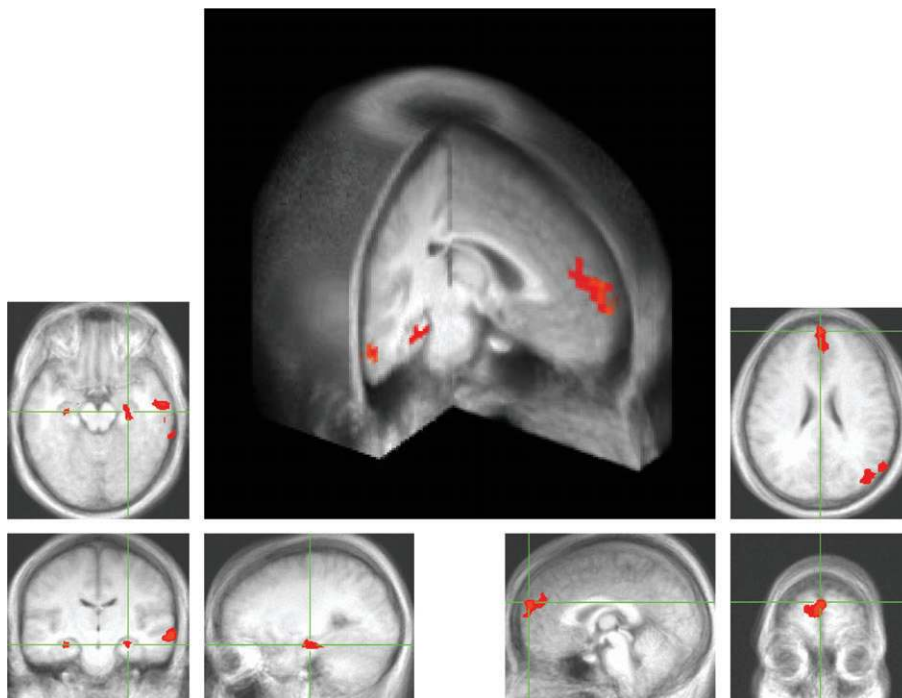
The results of our ANOVA also revealed main effects of memory outcome. As shown in Table 1, frontal and medial temporal areas were distinguished between encoding trials that resulted in later recognition from encoding trials that did not. The inferior frontal gyrus, in particular, showed increased activation on encoding trials that led to later forgetting versus those that led to remembering (see also Reber et al. 2002). Conversely, the inferior parietal lobule and parahippocampal gyrus showed greater activity on encoding trials for which the later outcome would be remembering versus trials for which the later outcome would be forgetting.

### Memory Instruction by Outcome

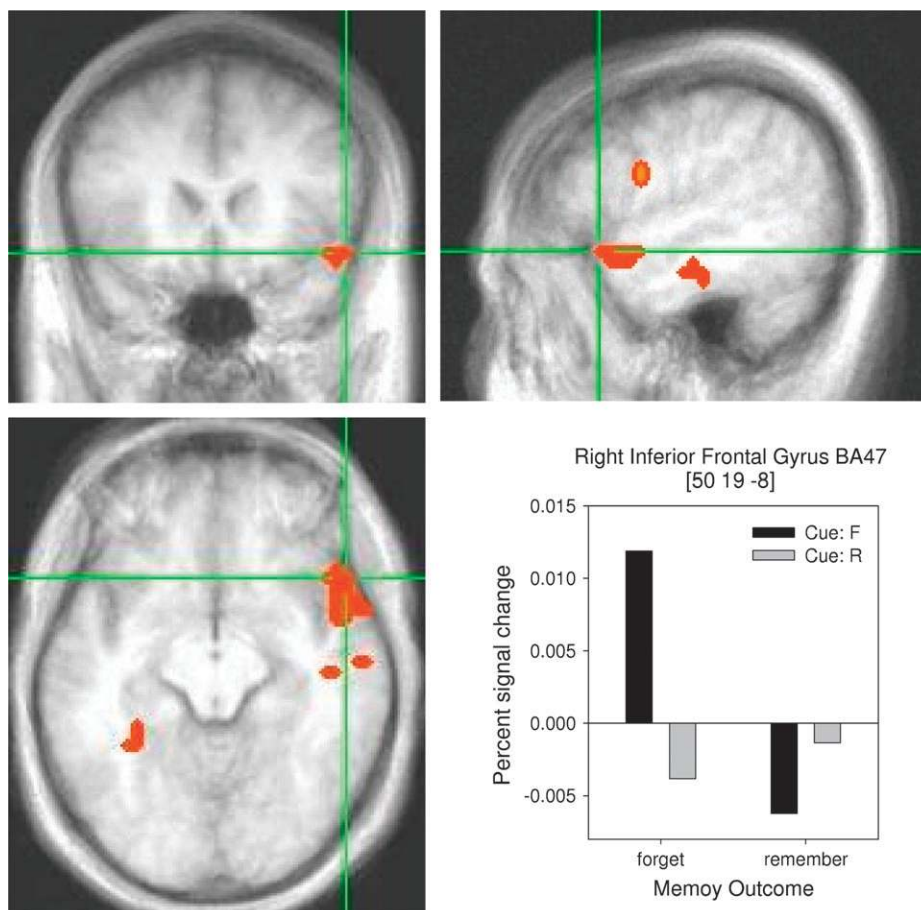
Memory instruction and outcome interacted significantly in several key memory-related areas. These included inferior frontal gyrus, insula, inferior parietal lobule, thalamus/pulvinar, parahippocampal gyrus, superior frontal gyrus, and inferior temporal gyrus (see also Table 1). Of these activations, only that in right, inferior parietal regions (Brodmann area [BA] 47) showed increased activity that was specific to the F-Forget condition (see Fig. 4). The insula (BA13), left-sided inferior parietal (BA40), and thalamus/pulvinar regions showed increased activity that might be characterized as predicting successful instantiation of intentions (see Fig. 5). These regions showed more activity in the F-Forget than the F-Remember condition and more activity in the R-Remember than the R-Forget condition. Thus, regardless of whether the intention was to forget or remember the item, these areas were more active when the intention was later successfully implemented relative to when it was not. Conversely, activity in the inferior frontal (BA45) and parahippocampal (BA 36) gyri appeared to predict failure to instantiate an intention (see Fig. 6). Activity in these areas was greater for F-Remember than for F-Forget and for R-Forget than for R-Remember. Contrast analyses were conducted to better understand the activity in the regions showing reliable interaction effects.

### Intentional Remembering

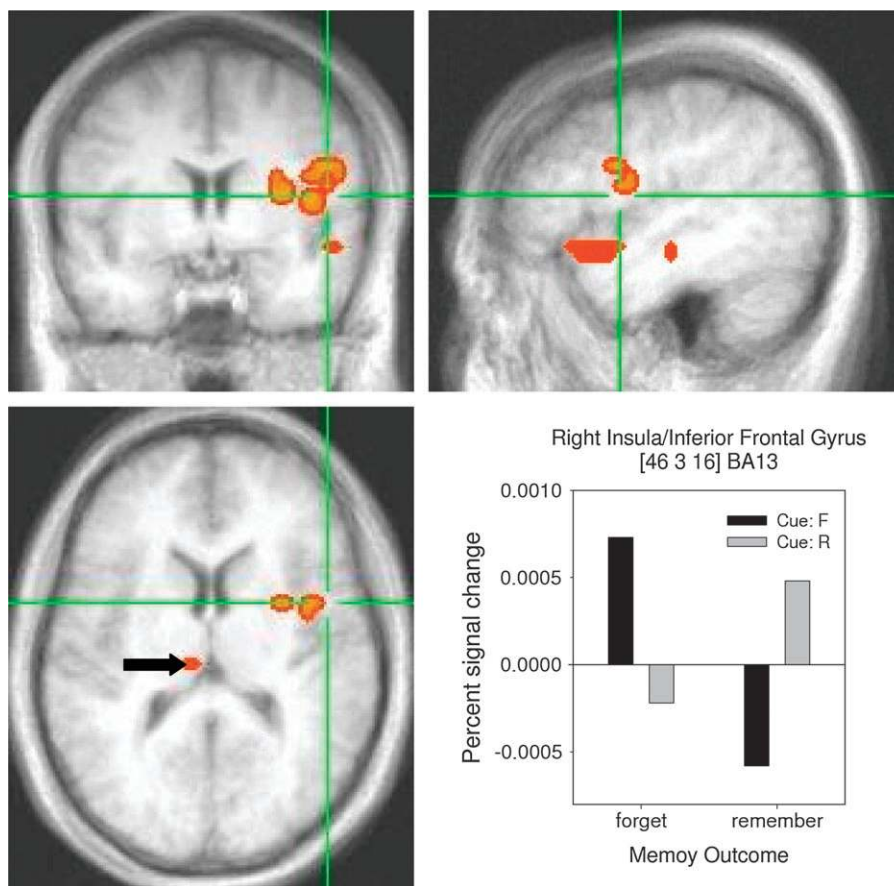
To assess the network underlying successful remembering, we compared study trials on which the attempt to intentionally commit a word to memory later resulted in recognition success to those that later resulted in failure (R-Remember-R-Forget). Our results replicate previous findings of activity in perirhinal cortex (Davachi et al. 2003). This contrast also revealed that in addition to activity in visual areas and the cerebellum, there was more activity in the middle frontal gyrus and in the cingulate gyrus while participants were encoding an R word they would later correctly recognize compared with one they would later



**Figure 3.** The main effect of Memory Instruction. The orthogonal pictures at the left detail the hippocampal activation. The orthogonal pictures at the right detail the frontal activation. These activations are also shown on the reconstruction in the center.



**Figure 4.** The interaction between Memory Instruction (Cue) and Outcome. The crosshairs indicate an area in right inferior frontal gyrus (BA47) that is preferentially active in the F-Forget (directed forgetting) condition.



**Figure 5.** The interaction between Memory Instruction (Cue) and Outcome. The crosshairs indicate an area in right insula/inferior frontal gyrus that was more active when participants were going to succeed in their intention (F-forget or R-remember) than when they were going to fail (R-forget or F-remember). The activation in this area is graphed in the lower right. The same pattern was evident in the thalamus, which can be seen in the axial slice and is denoted by the arrow.

forget (see Table 1). The same was true of the inferior parietal lobule and the thalamus/pulvinar.

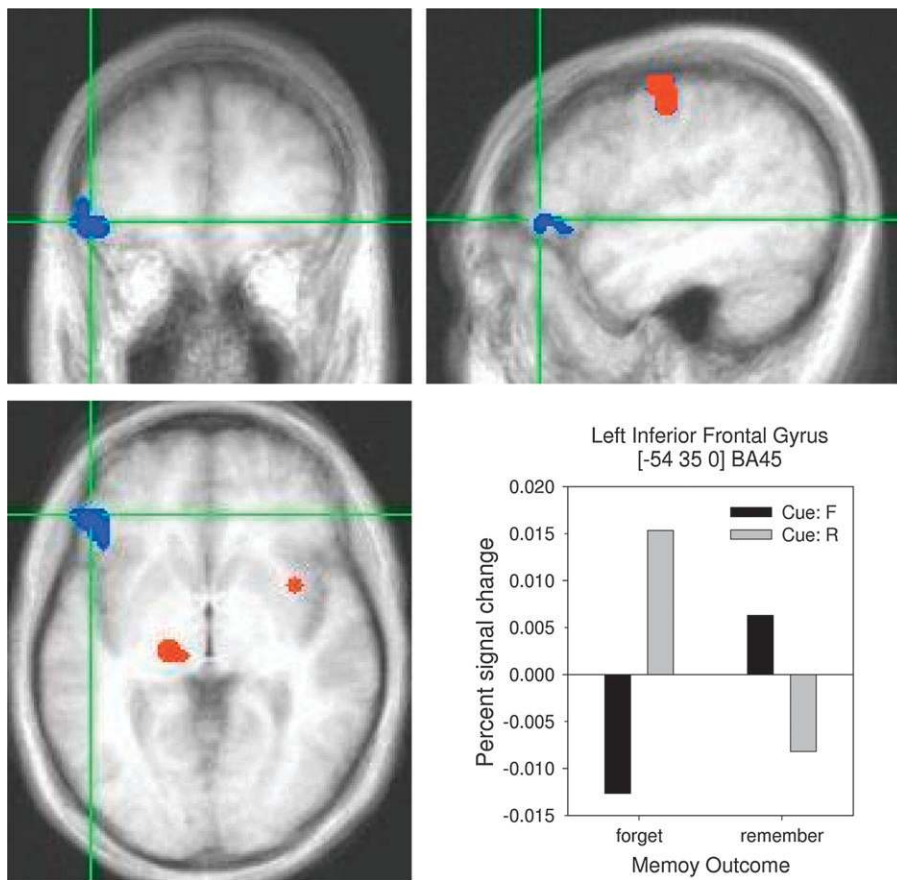
### **Intentional Forgetting**

To assess the areas associated with intentional forgetting, we compared F trials at study that later resulted in successful forgetting with those that resulted in failure to forget (F-Forget-F-Remember). According to the common incarnation of the selective rehearsal account, forgetting occurs in an item-method paradigm because participants drop F items from the rehearsal set and therefore fail to fully encode them (passive decay). If this were the case, then the incidental remembering that occurred for F-Remember items should be associated with mechanisms involved in episodic encoding; by comparison, successful forgetting in the F-Forget condition should either not involve these mechanisms at all or should engage them weakly and/or for a shorter duration. Thus, if successful intentional forgetting were due simply to a lack of encoding, then subtracting the activation associated with F-Remember items from the activation associated with F-Forget items should result in no positive activations. Instead, one would expect this contrast to yield “negative” activations in areas associated with episodic encoding. This is not what we found, however. When the intention to forget successfully prevented a word from being committed to memory, there was more activity in several areas compared with when the intention failed and the word was later recognized (see Table 1). These areas included the

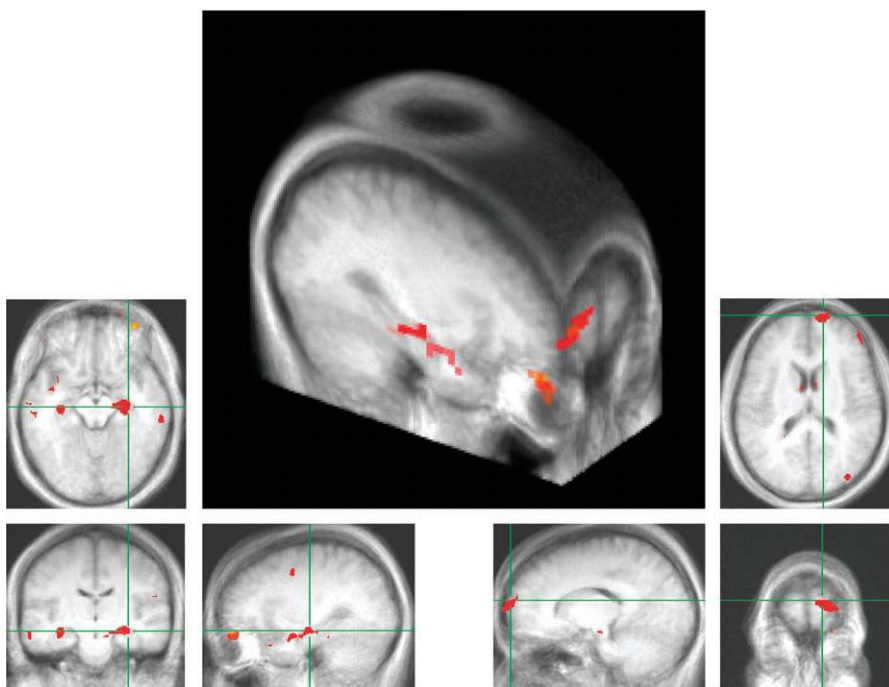
superior/middle frontal gyrus and inferior frontal gyrus. Importantly, inferior frontal gyrus has also been implicated in successful stopping of overt behavior (e.g., Aron et al. 2003).

### **Intentional Forgetting versus Unintentional Forgetting**

If it were the case that intentional forgetting resulted from a simple failure to encode the forgotten F word, then similar failures to encode R words would be expected to result in similar patterns of neural activity. This was not the case, however. We compared study trials on which participants were instructed to forget the word and subsequently failed to recognize it with study trials on which they were instructed to remember the word, but subsequently failed to recognize it (F-Forget-R-Forget). As shown in Figure 7 (and also in Table 1), this comparison revealed increased activity in the parahippocampal gyrus/hippocampus and the superior frontal gyrus. The fact that unique activations were revealed after this subtraction confirms that intentional forgetting and unintentional forgetting are distinguishable. Nevertheless, this comparison revealed that some of the activity associated with intentional forgetting occurred in the network associated with unintentional forgetting (Wagner and Davachi 2001); of the regions previously implicated in unintentional forgetting (posterior cingulate, bilateral inferior parietal, and medial parietal cortices), we found activity in the inferior parietal lobule and posterior cingulate cortex.



**Figure 6.** The interaction between Memory Instruction (Cue) and Outcome. The crosshairs indicate an area in left inferior frontal gyrus that was more active when participants were going to fail in their intention (R-forget or F-remember) than when they were going to succeed (F-forget or R-remember). The activation in this area is graphed in the lower right.



**Figure 7.** The F-Forget-R-Forget comparison. Activations to survive multiple corrections included hippocampus and frontal gyrus.



### ***Intentional Remembering versus Unintentional Remembering***

A similar (exploratory) contrast was performed to compare intentional and unintentional remembering. We examined whether activity during study differentiates remembering that occurs intentionally and remembering that occurs in the absence of such an intention (R-Remember-F-Remember). In both cases, the behavioral outcome was the same: A study word was correctly recognized as old at test. However, in the case of the R-Remember condition, the word was remembered because the participant intended to remember it; in the case of the F-Remember condition, the word was remembered despite the fact that the participant intended to forget it. In this comparison, intentional remembering was associated with greater activity in superior frontal gyrus and in postcentral gyrus (see Table 1).

### **Discussion**

Intentional forgetting prevents outdated or irrelevant information from interfering with memory for relevant information (cf. Bjork 1989). We presented participants with words that they were instructed to remember or forget on a trial-by-trial basis. Our goal was to determine whether forgetting in such a paradigm is an active process that relies on neural structures commonly associated with attention/executive control or whether forgetting represents a simple failure to encode. Event-related fMRI data were acquired during the study phase when the intention to remember or forget was formed and these were sorted post hoc according to subsequent recognition performance.

### ***Is Intentional Forgetting Different from Unintentional Forgetting?***

Our view is that unintentional forgetting reflects encoding that is insufficient to support later recognition, it is a failure to remember. Intentional forgetting, by contrast, is an active cognitive process that prevents words from being committed to memory (cf. Hourihan and Taylor 2006). Thus, to distinguish intentional from unintentional forgetting, it is necessary to demonstrate that intending to forget is not simply the obverse of intending to remember. Several lines of evidence support this distinction. First, the main effect of memory instruction revealed important differences in encoding activations following the receipt of R and F instructions. In particular, we found a network of areas that was more active when participants received an F instruction relative to when they received an R instruction. Indeed, the majority of the differences in this main effect were in this direction (i.e., more activity for F instructions than for R instructions). This suggests that when participants receive an F instruction, they 1) activate substantially the same mechanisms active in response to an R instruction and then 2) employ additional mechanisms to intentionally forget the item. Perhaps even more striking was the Memory Instruction by Outcome interaction that showed increased activity in the right inferior frontal gyrus for the F-Forget condition relative to other conditions. Activity in this region appears to be specific to successful directed forgetting in this paradigm. Finally, in the contrasts on the Memory Instruction by Outcome interaction, we determined that intentional forgetting of F words produced unique activations compared with failures to encode R words (i.e., unintentional forgetting). Some of the activity associated with intentional forgetting occurred in areas known to be

involved in unintentional forgetting (e.g., inferior parietal lobule and posterior cingulate cortex) and some occurred in unique areas (e.g., parahippocampal gyrus/hippocampus and the superior frontal gyrus [BA 10/11]).

The activity in BA 10/11 offers a possible avenue for the interpretation of these effects. This area has been shown to be more active when participants perform tasks based on external visual stimuli compared with when they perform the same tasks based on internally generated mental representations (e.g., Gilbert et al. 2005, 2006), suggesting that activity in this part of prefrontal cortex supports the engagement/focusing of attention on external stimuli, particularly during low-demand tasks that might otherwise be expected to lead to “daydreaming” (see Burgess et al. 2005 for a review). Our finding of increased activation in BA10/11 therefore suggests that intentional forgetting might involve deliberately focusing attention on the external environment, rather than directing attention toward internally represented associations that might lead to deep processing.

### ***Successful versus Unsuccessful Intentions***

One of the strengths of the design used here is that it allowed us to assess the interaction of intentions and outcomes (see also Reber et al. 2002). Thus, we identified a number of areas that were associated with the successful instantiation of an intention to remember or forget a word. These areas included the right insula, left-sided inferior parietal areas, and the thalamus. Previous research has shown that these areas form part of an attentional control network (e.g., Fan et al. 2005). This suggests that the successful instantiation of an intention—whether an intention to remember or to forget—depends critically on the engagement of attentional resources.

Contrast analyses further revealed that this attentional network was primarily active during encoding of R words that would be successfully remembered, inasmuch as the insula and inferior parietal areas were found to be active in the R-Remember *minus* R-Forget comparison. Moreover, we replicated activity in perirhinal cortex (Davachi et al. 2003) that is associated with successful encoding. This contrast also revealed that in addition to activity in visual areas and the cerebellum, there was more activity in the middle frontal gyrus and in the cingulate gyrus while participants were encoding an R word they would later correctly recognize compared with one they would later forget (see Table 1).

Conversely, activity in left inferior frontal regions and left parahippocampal regions predicted later failure to instantiate intentions. Thus, when participants were attempting to forget a word, activity in these areas (at encoding) predicted later recognition of that word; when participants were attempting to remember a word, activity in these areas predicted later forgetting of that word. Although activity in parahippocampus might well be expected to predict incidental remembering following an F instruction, it is unclear why it would also predict unintentional forgetting following an R instruction. One possibility is that failed intentions in this paradigm reflect the use of maintenance rather than elaborative rehearsal on affected trials. Maintenance rehearsal of F words would lead to incidental memory on some trials; such incidental learning is supported by the fact that recognition of F-instructed words is greater than the false alarm rate for foils in the behavioral data. Maintenance rehearsal of R words would also lead to occasional incidental learning; however, these trials would be sorted into the R-

Remember condition. When no enduring trace was formed, the use of maintenance rehearsal on R trials would lead to memory failures, by virtue of being a shallow level of processing, and would be sorted into the R-Forget condition. Thus, compared with R-Remember trials on which elaborative processing was likely engaged on the majority of trials and F-Forget trials on which elaborative rehearsal was actively prevented, F-Remember and R-Forget trials may have involved maintaining and refreshing items through rote repetition. The observed prefrontal activity is consistent with refreshing and maintaining verbal items (e.g., Wagner et al. 2001; Johnson et al. 2005). The additional parahippocampal activity may reflect the attempt to relate these maintained items to the R and F instructions (see Davachi 2006 for a review) so as to attempt (albeit unsuccessfully) to carry out the intention. Whether this proves to be true or not, the finding that activity in right insula predicts success, whereas activity in left inferior frontal regions predicts failure represents an important step forward in the functional differentiation of frontal structures.

### ***Is Intentional Forgetting Achieved by Active Suppression?***

The above-mentioned activity in parahippocampus/hippocampus might lead one to question whether the activity on F trials is associated with the reactivation and cumulative rehearsal of R words from previous trials, rather than mechanisms involved in active forgetting. To the extent that cumulative rehearsal on F trials engages the same mechanisms as those involved in rehearsal on R trials, the main effect of Memory Instruction argues against this strategy: As noted above (see also Table 1), receiving an instruction to forget activates unique areas relative to receiving an instruction to remember. These findings do not negate the possibility that participants used a cumulative rehearsal strategy on F trials, but—to the extent that such activity was equally demanding on R and F trials—activity associated with such a strategy would be eliminated in this comparison. Of course, it is possible that the differences we observed were precisely because cumulative rehearsal on F trials was not equivalent to rehearsal on R trials. On R trials, participants may have been engaged primarily in the elaboration of the item, whereas on F trials, participants may have been engaged in episodic retrieval of R items from previous trials. Certainly, in the contrasts on the Memory Instruction by Outcome interaction, intentional remembering (R-Remember-F-Remember) and intentional forgetting (F-Forget-F-Remember) both produce activations in nearby areas of the superior frontal gyrus (areas BA9 and BA11). Nevertheless, intentional forgetting produces activations in many additional areas, including inferior/middle frontal gyrus, inferior parietal lobule, parahippocampal gyrus/hippocampus, and posterior cingulate. Together, these results suggest that even if intentional forgetting involves cumulative rehearsal of R words, this strategy is a by-product of the F instruction and not the mechanism by which successful intentional forgetting occurs.

Likewise, passive decay is not the sole mechanism by which intentional forgetting occurs. The main effect of Memory Instruction demonstrates that receiving an F instruction is not the obverse of receiving an R instruction. Instead, there are unique activations associated with an F instruction in areas known to be involved in memory formation (see Buckner et al. 1999). Importantly, the majority of these activations are greater

following an F than following an R instruction. This argues that an active cognitive process is engaged by the F instruction—the F instruction is not merely associated with decreased activity in regions involved in memory formation (see also Ullsperger et al. 2000). This conclusion is further supported by contrasts on the Memory Instruction by Outcome interaction.

A dominant feature of the present results is that frontal areas are strongly activated by the intention to forget and by the successful instantiation of that intention. It has been well established that frontal areas work in conjunction with medial temporal areas in the formation of new memories (see Buckner et al. [1999] for a review). Frontal activity is therefore thought to be requisite for successful encoding. Indeed, decreased frontal lobe activity associated with aging (Cabeza et al. 1997; Rosen et al. 2002; Stebbins et al. 2002) or with disorders such as schizophrenia (Hofer et al. 2003; Ragland et al. 2004) is frequently implicated when encoding difficulties are observed in these populations. What is clear from our data, however, is that frontal activity is not only involved in the creation of memories but also in preventing unwanted traces from surpassing threshold for behavioral recognition. This raises the possibility that frontal areas may not necessarily be engaged in the encoding of memories per se but rather in the selection of episodes to guide behavior. Whether this selection involves attentional processes operating on the contents of working memory (cf. Zacks et al. 1996) remains to be determined.

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### **Appendix A: words used for memory task**

hillside  
apple  
charter  
steamer  
affection  
examination  
golf  
admiral  
arrow  
potato  
salary  
warmth  
economy  
explanation  
victim  
hide  
breeze

rod  
facility  
beast  
menace  
quest  
ankle  
swamp  
diamond  
coffee  
claw  
clock  
creature  
fork  
insect  
wine  
pledge  
fisherman  
cradle  
profession  
volume  
monk  
property  
errand  
weapon  
poetry  
origin  
odor  
safety  
ink  
blossom  
nail  
recognition  
costume  
occasion  
vision  
hint  
rattle  
wheat  
unit  
advice  
palace  
impulse  
fun  
atmosphere  
corn  
troops  
kettle  
folly  
grandmother  
prison  
maiden  
butcher  
excuse  
oven  
convention  
moisture  
garments  
welfare  
pressure  
artist  
coin  
science  
poverty  
instrument  
forehead  
coast  
vapor  
justice  
salute  
sickness  
devil

expression  
oxygen  
engagement  
style  
reaction  
ceremony  
mischief  
banner  
author  
headquarters  
owner  
fowl  
colony  
destruction  
background  
hotel  
marriage  
bowl  
dirt  
monarch  
captive  
sunset  
attendant  
infant  
prosperity  
pipe  
jail  
agreement  
pepper  
charm  
inn  
bosom  
bar  
boulder  
contents  
discipline  
settler  
research  
thorn  
tobacco  
candidate  
sulfur  
tablespoon  
decree  
thief  
instance  
lemon  
pupil  
harp  
permission  
hammer  
toy  
assault  
humor  
goddess  
appearance  
mule  
competition  
hoof  
miracle  
banker  
piano  
exhaust  
legislation  
toast  
institute  
ghost  
geese  
comrade  
snake  
enterprise

prairie  
elbow  
shock  
metal  
slipper  
flood  
physician  
fabric  
tragedy  
gem  
cabin  
bloom  
disaster  
lad  
oats  
frog  
barrel  
angle  
code  
candy  
agony  
lump  
crime  
situation  
engine  
singer  
vest  
string  
flag  
harness  
contract  
stain  
injury  
interview  
comparison  
speaker  
breast  
fox  
factory  
dawn  
cell

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