

# Fractionation of the Component Processes Underlying Successful Episodic Encoding: A Combined fMRI and Divided-attention Study

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## Abstract

■ Considerable evidence suggests that attentional resources are necessary for the encoding of episodic memories, but the nature of the relationship between attention and neural correlates of encoding is unclear. Here we address this question using functional magnetic resonance imaging and a divided-attention paradigm in which competition for different types of attentional resources was manipulated. Fifteen volunteers were scanned while making animacy judgments to visually presented words and concurrently performing one of three tasks on auditorily presented words: male/female voice discrimination (control task), 1-back voice comparison (1-back task), or indoor/outdoor judgment (semantic task). The 1-back and semantic tasks were designed to compete for task-generic and task-specific attentional resources, respectively. Using the “remember/know” procedure, memory for the study words was assessed after 15 min. In the control condition, subsequent

memory effects associated with later recollection were identified in the left dorsal inferior frontal gyrus and in the left hippocampus. These effects were differentially attenuated in the two more difficult divided-attention conditions. The effects of divided attention seem, therefore, to reflect impairments due to limitations at both task-generic and task-specific levels. Additionally, each of the two more difficult divided-attention conditions was associated with subsequent memory effects in regions distinct from those showing effects in the control condition. These findings suggest the engagement of alternative encoding processes to those engaged in the control task. The overall pattern of findings suggests that divided attention can impact later memory in different ways, and accordingly, that different attentional resources, including task-generic and task-specific resources, make distinct contributions to successful episodic encoding. ■

## INTRODUCTION

A substantial behavioral literature indicates that attentional resources are required for the formation of an episodic memory representation. The importance of the relationship between attention and episodic encoding is attested by a wide variety of studies demonstrating that later memory for study items is harmed when attention is shared between a study task and a secondary, distractor task (e.g., Fernandes & Moscovitch, 2000; Gardiner & Parkin, 1990; Park, Smith, Dudley, & Lafronza, 1989; Kellogg, Bourne, & Cocklin, 1982; Anderson & Craik, 1974; Baddeley, Scott, Drynan, & Smith, 1969; Murdock, 1965). Such “dual-task” or “divided-attention” manipulations have complex effects on later memory performance. For example, divided attention during encoding has a greater impact when memory is later assessed with free or cued recall than with recognition (see Craik, 2001 for review), and is more detrimental to recollection than to familiarity-driven recognition (for review, see Yonelinas, 2002). Divided attention during encoding is, however, equally harmful to memory for items and for interitem associations (Naveh-Benjamin, Guez, & Marom, 2003).

In addition to behavioral evidence such as that cited above, the findings of two recent functional magnetic resonance imaging (fMRI) studies (Uncapher & Rugg, 2005a; Kensinger, Clarke, & Corkin, 2003) employing the “subsequent memory procedure” also suggest that there is an intimate relationship between attention and the formation of durable memory representations. In both studies, subsequent memory effects elicited by study items were investigated according to whether subjects were concurrently performing a more- versus a less-demanding concurrent task. In both cases, items studied concurrently with the more demanding task were less likely to be remembered on the subsequent memory test. As is discussed below, however, the fMRI findings suggest that the detrimental effects of divided attention appear to have arisen from different mechanisms in the two studies.

In the study of Kensinger and colleagues, volunteers were instructed to make abstract/concrete decisions to visually presented study words while concurrently performing one of two auditory discrimination tasks. In each secondary task, volunteers discriminated between two auditory patterns, with the demands of the easy and the hard conditions manipulated by the degree of similarity between the patterns. The authors reported that performance of the hard divided-attention condition led

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to the abolition of several of the subsequent memory effects that were evident in their easy condition, such that successful encoding under the hard condition was associated with only a subset of the effects evident under relatively full attention. The regions that exhibited attenuated subsequent memory effects—the left inferior frontal gyrus (IFG) and the hippocampus—have been implicated in the operations that support later recollection when semantically encoded study items were fully attended (e.g., Brassens, Weber-Fahr, Sommer, Lehmbeck, & Braus, 2006; Staresina & Davachi, 2006; Uncapher, Otten, & Rugg, 2006; Uncapher & Rugg, 2005b; Kensinger & Corkin, 2004; Ranganath et al., 2004; Otten, Henson, & Rugg, 2001). Kensinger et al. (2003) further reported that a region in the parahippocampal gyrus—previously associated with the encoding of items later recognized on the basis of familiarity (Gold et al., 2006; Kensinger & Schacter, 2006; Uncapher & Rugg, 2005b; Ranganath et al., 2004; Henson, Rugg, Shallice, Josephs, & Dolan, 1999)—exhibited equivalent subsequent memory effects across the two divided-attention conditions. Together with the results of a companion behavioral study, these findings led the authors to argue that recognition memory was disrupted because the harder of their secondary tasks competed for the same processing resources that selectively supported recollective (rather than familiarity-based) encoding.

Similarly to Kensinger et al. (2003), Uncapher and Rugg (2005a) also required their volunteers to perform semantically oriented (animacy) judgments on visually presented study words. Unlike the prior study, however, the concurrent task items comprised discrete verbal stimuli—the digits 1 through 10 spoken in either a male or a female voice. In the less demanding of the secondary tasks, volunteers were required to indicate whenever a digit was spoken by the female. The more demanding task required one-back judgments as to whether two consecutive digits were both even or both odd. In contrast to Kensinger and colleagues, we failed to find differences in the magnitude of any subsequent memory effects between the two secondary task conditions. Rather, there were two regions where activity elicited by the study and secondary task items demonstrated a reciprocal relationship according to the difficulty of the secondary task. Whereas study item activity was attenuated during performance of the harder of the two tasks, the activity elicited by the distracting items was enhanced. The regions where these effects were observed—the dorsolateral prefrontal cortex and the superior parietal cortex—have been heavily implicated in the support of task-generic, executive processes. Accordingly, these reciprocal effects were interpreted as evidence that executive processes were “traded-off” between the two tasks, leading to a reduction in the likelihood that processes supporting episodic encoding would be engaged under the more difficult secondary task condition.

Taken together, the studies of Uncapher and Rugg (2005a) and Kensinger et al. (2003) suggest that withdrawal of attentional resources away from a study task can have variable effects on encoding-related neural activity and, by implication, variable effects on the cognitive processes that together support successful encoding. In Kensinger et al., withdrawal of attention appeared to reduce the availability of processing resources supporting semantically mediated encoding of study items (“task-specific” processes); in Uncapher and Rugg, divided attention appears to have interfered with more generic processes, responsible perhaps for the allocation of task-specific resources (“task-generic” processes).

The disparate findings reported by Uncapher and Rugg (2005a) and Kensinger et al. (2003) imply that successful episodic encoding depends on the recruitment of multiple attentional resources. The strength of this conclusion is weakened, however, because of the very different experimental procedures that were employed in the two studies. Arguably, the most important difference concerns the temporal contingency between the presentation of study words and distracting events. Whereas Kensinger et al. timed the presentation of their auditory “target” items so they always overlapped the visual study words, the timing of our auditory distractors ensured that they never overlapped with study items. These different presentation contingencies would have led to marked differences in the amount of perceptual interference induced by the dual-task manipulations in each study, as well as differences in how processing resources were allocated between the tasks. Therefore, whereas the disparate findings of the two studies are consistent with the idea that different attentional resources make distinct contributions to episodic encoding, we cannot rule out the possibility that the findings merely reflect differences in the strategies adopted by volunteers in the two experiments to cope with the demands of the respective dual-task designs. Thus, on the basis of these findings, it would be premature to conclude that the processes supporting episodic encoding can be dissociated by dual-task manipulations.

The aim of the present study was to test the hypothesis that multiple attentional resources are recruited during successful episodic encoding. We compared the impact on fMRI subsequent memory effects of competition for task-specific versus task-generic processing resources. Crucially, we employed a within-subjects design, and held constant such variables as stimulus materials, timing parameters, and so forth, while varying the nature of the secondary tasks. Thus, the confounds bedeviling the interpretation of the disparate findings reported by Uncapher and Rugg (2005a) and Kensinger et al. (2003) were eliminated. In addition, and unlike in the two preceding studies, we adopted a test procedure that allowed remembered study items to be segregated according to whether they were recollected, or recognized solely on the basis of familiarity. By adopting this procedure, we were able to

address the possibility that, in the two previous experiments, which based their subsequent memory analyses on undifferentiated recognition judgments, there was an imbalance in the relative contributions of recollection and familiarity to subsequent memory effects in the easier and the harder divided-attention conditions (as was suggested by Kensinger and colleagues on the basis of their separately conducted behavioral study). Thus, an additional advantage of the present experiment over its predecessors is that we could investigate how manipulations of the availability of different types of attentional resource (task-specific vs. task-generic) modulated subsequent memory effects associated specifically with successful recollection.

## METHODS

This study was approved by and performed in accordance with the Institutional Review Board of the University of California at Irvine (UCI).

### Participants

Twenty-three volunteers (10 men; 18–30 years of age, mean = 22 years) gave informed consent to participate in the experiment. All volunteers reported themselves to be right-handed, in good general health, with no history of neurological disease or other contraindications for MR imaging, and to have learned English as their first language. Volunteers were recruited from the UCI community and remunerated for their participation. Three volunteers' data were excluded because of inadequate memory performance ( $>2$  *SDs* above the sample mean for false alarms), one volunteer's data were excluded due to the volunteer falling asleep during the scanning session, and four volunteers' data were excluded for contributing fewer than 10 trials per condition in one or more critical experimental conditions (see Data analysis below).<sup>1</sup>

### Stimulus Materials

#### *Study Task Stimuli*

Stimuli were drawn from a pool of 489 words (four to nine letters long; mean written frequency between 1 and 30 counts per million; Kucera & Francis, 1967). This pool was used to create nine lists of 50 items each, with half the words in each list representing animate objects and the other half representing inanimate objects. Study lists of 300 critical items were created from six of the lists, with an additional 12 items serving as buffers. One third (100) of the critical items were presented in the control condition, another third were presented in the “1-back” condition (see below), and the remaining third were presented in the “semantic” condition. The final three

word lists were used to create a list of 150 new items, with three additional items used as buffers. Word lists were rotated between study and test conditions across subjects. A separate practice study list of 24 items was created from the remainder of the word pool.

All words were presented visually in white uppercase letters on a black background centered on fixation. They subtended maximum horizontal and vertical visual angles of 8° and 1.5°, respectively. During the study phase, words were presented via VisuaStim (Resonance Technology, Northridge, CA, USA) XGA MRI-compatible head-mounted display goggles with a 30° field of view and a resolution of 640 × 480 pixels. During the test phase, words were presented on a computer monitor with equivalent display parameters (e.g., size, font, and background/text colors).

#### *Secondary Task Stimuli*

Secondary task stimuli consisted of 330 concrete nouns presented auditorily, each spoken by a male or a female. Words used for auditory stimuli were different from those for the study stimuli. Half the words represented items that would most likely be found outdoors, whereas the other half were most likely to be found indoors. Half of each word class (indoor or outdoor) was spoken by a male and the other half by a female. Stimuli were recorded in the laboratory, edited to a constant sound pressure level, and filtered to remove ambient noise (<http://audacity.sourceforge.net>). Auditory stimuli were presented binaurally via MR-compatible headphones and did not exceed 500 msec in duration. Presentation volume was adjusted in the scanner to a comfortable listening level for each volunteer prior to scanning.

From the auditory item pool, two lists of 152 words each were created. Each list comprised 38 items from each of the four item classes (indoor spoken by a man, outdoor spoken by a man, indoor spoken by a woman, outdoor spoken by a woman). One list was used for each of the three conditions of one scanning session, with the second used in the other scanning session (see below). Lists were counterbalanced across the first and second scanning sessions across volunteers. The order of the items within each list was pseudorandomized for each condition, such that no more than three target items (see below) occurred consecutively. The probability of occurrence of a target item in each list was .50. The remaining 26 auditory stimuli were used for each of the three conditions during the practice study session.

## Experimental Tasks and Procedures

### *Procedure at Study*

Scanning occurred during the study phase only. Instructions and practice sessions were given outside the scan-

ner. The study phase of the experiment proper consisted of two consecutive scanning sessions. In each session, the study phase was performed in three blocks: one in conjunction with the control secondary task, a second in conjunction with the 1-back secondary task, and the third in conjunction with the semantic secondary task. The ordering of the secondary task blocks was consistent across sessions and counterbalanced across subjects. The study task was identical in all three conditions: Volunteers were instructed to make animacy decisions to the visually presented words and depress buttons with their index (“animate”) and middle (“inanimate”) fingers of one hand accordingly. The secondary task for the control condition required volunteers to depress a button with the index finger of the opposite hand whenever auditorily presented words were spoken by a female, regardless of the identity of the word. The 1-back secondary task required a button press whenever the currently presented and immediately preceding words were spoken in the same voice, again regardless of the identity of the word. The semantic secondary task required a button press whenever a word was spoken whose referent was likely to be found outdoors, regardless of voice. Assignment of hands to each task was counterbalanced across subjects. Volunteers were instructed to place equal emphasis on the study and secondary tasks, and to respond as quickly and as accurately as possible.

The beginning of each study block was indicated by a 10-sec cue (“Female?,” “Same voice?,” or “Outdoor” for control, 1-back, and semantic conditions, respectively), followed by a central fixation cross. Visual word stimuli were presented for 300 msec, replacing a baseline fixation cross that was present throughout the interword interval. The word stimulus onset asynchrony (SOA) was stochastically distributed with a minimum SOA of 3000 msec modulated by the addition of one-third randomly intermixed null trials (Josephs & Henson, 1999). The stimuli were presented in pseudorandom order, with no more than three trials of one item type (animate, inanimate, or null) occurring consecutively. Each block began with two buffer words, and consisted of 50 critical words (for a total of 300 critical study items across six blocks). Auditory stimuli were presented with an SOA that varied randomly between 1000 and 2000 msec (mean = 1508 msec), and were timed such that the presentations of study and auditory stimuli did not overlap.

#### *Procedure at Test*

A surprise recognition memory test was administered outside the scanner approximately 15 min after the conclusion of the last study block. Volunteers were instructed to decide whether they recollected seeing the word during the study phase (a *remember* response), felt that the word was familiar from the previous study phase but could not recollect any contextual information from the study episode (a *know* response), or judged

the word to be new (a *new* response). The remember/know distinction was explained using standard instructions (e.g., Rajaram, 1993), clarified with examples. Responses were made using the index (remember), middle (know), and ring (new) fingers of their right hand. Volunteers were instructed to respond quickly without sacrificing accuracy.

The recognition test was administered in three consecutive blocks with short rest periods. All 300 critical words presented during the study phase (old items) were presented, interspersed among 150 unstudied words (new items). One additional new buffer item was added to the beginning of each test block. On each trial, a white fixation cross was presented on a black background for 500 msec, the screen blanked for 100 msec and the test word was presented for 300 msec. The screen remained blank until the volunteer indicated a response with one of the three appropriate buttons. Old and new items were presented pseudorandomly with no more than three trials of one item type occurring consecutively. Words were presented in the same font and size as during the study phase.

#### **fMRI Scanning**

A Philips Eclipse 1.5-T MR scanner (Philips Medical Systems, Andover, MA, USA) was used to acquire both  $T_1$ -weighted anatomical volume images ( $256 \times 256$  matrix,  $1 \text{ mm}^3$  voxels, SPGR sequence) and  $T_2^*$ -weighted echo-planar images [ $64 \times 92$  matrix,  $2.6 \times 3.9$  mm pixels, echo time (TE) of 40 msec] with blood oxygenation level-dependent (BOLD) contrast. Each EPI volume comprised twenty-seven 3-mm-thick axial slices separated by 1.5 mm, positioned to give full coverage of the cerebrum and most of the cerebellum. Data were acquired in two sessions, each composed of 310 volumes with a repetition time (TR) of 2.5 sec/volume. Volumes within sessions were acquired continuously in a descending sequential order. The first four volumes of each session were discarded to allow tissue magnetization to achieve a steady state. The 3.0-sec SOA for critical study items allowed for an effective sampling rate of the hemodynamic response of 2 Hz.

#### **Data Analysis**

Data preprocessing and statistical analyses were performed with Statistical Parametric Mapping (SPM2, Wellcome Department of Cognitive Neurology, London, UK; [www.fil.ion.ucl.ac.uk](http://www.fil.ion.ucl.ac.uk); Friston et al., 1995) implemented in MATLAB6 (The Mathworks, Inc., USA). The time series for voxels within each slice were realigned temporally to the acquisition of the middle slice in time, and all volumes were realigned spatially to the first volume. Inspection of movement parameters generated during spatial realignment indicated that no volunteer moved more than 3 mm

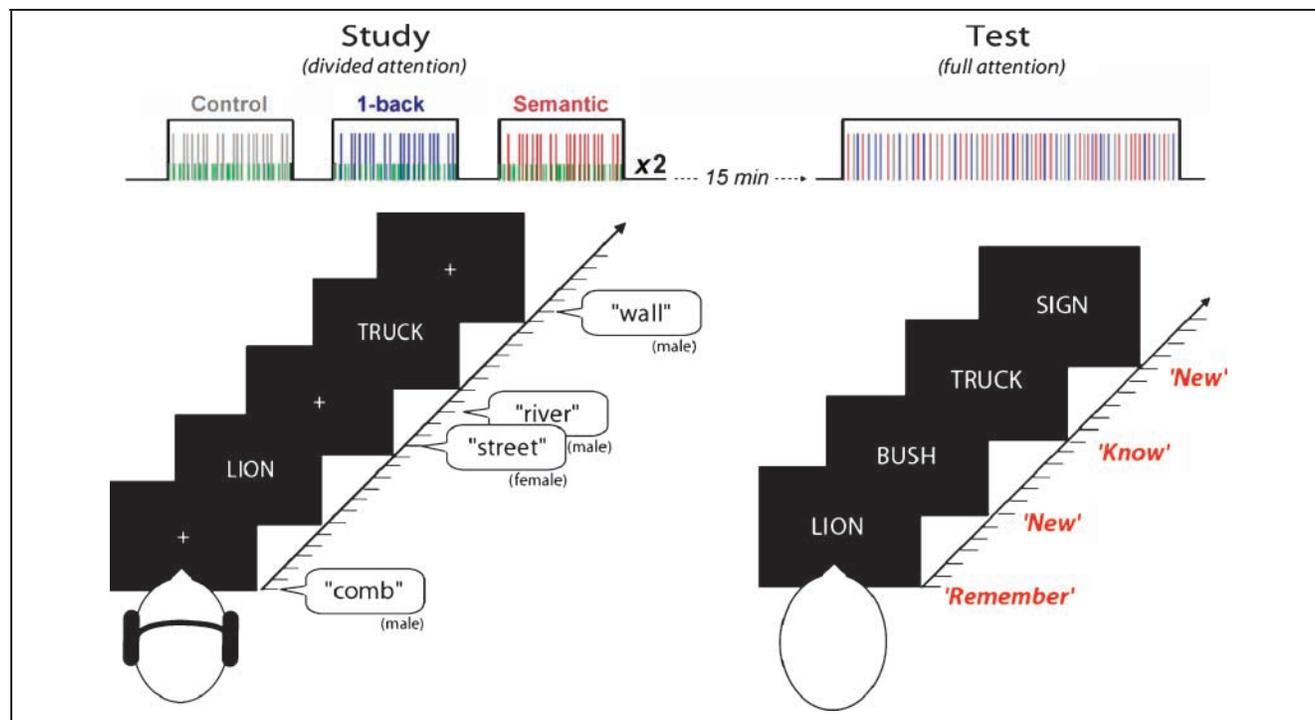
in any direction during any session. Resulting images were spatially normalized to a standard EPI template on the basis of the Montreal Neurological Institute (MNI) reference brain (Cocosco, Kollokian, Kwan, & Evans, 1997) and resampled into  $3\text{-mm}^3$  voxels using nonlinear basis functions (Ashburner & Friston, 1999). Image volumes were concatenated across sessions (comparisons of concatenated vs. nonconcatenated designs revealed qualitatively similar patterns of activation). Normalized images were smoothed with an isotropic 8-mm full-width half-maximum Gaussian kernel. The  $T_1$  anatomical volumes were coregistered to the mean EPI volume and normalized to a standard  $T_1$  template of the MNI brain.

Statistical analyses were performed in two stages of a mixed effects model. Study task and secondary (auditory) task stimuli were presented as discrete, nonoverlapping events (see Figure 1), permitting analyses to be conducted in a fully event-related design. In the first stage, neural activity elicited by the study and secondary task items was modeled by delta functions (impulse event) at stimulus onset. These functions were then convolved with a canonical hemodynamic response function (HRF) and its temporal and dispersion derivatives (Friston et al., 1998) to yield regressors in a General Linear Model that modeled the BOLD response to each event type. The two derivatives model variance in latency and duration, respec-

tively. Analyses of the parameter estimates pertaining to these derivatives added no theoretically meaningful information to that contributed by the HRF, and are not reported (results are available from the corresponding author upon request).

The following event types of interest were defined for each study session; all words studied under control concurrent task conditions later accorded a remember ( $R_{\text{control}}$ ), know ( $K_{\text{control}}$ ), or new ( $M_{\text{control}}$ ) response (regardless of study performance), analogous event types for the 1-back and semantic conditions ( $R_{1\text{-back}}$ ,  $K_{1\text{-back}}$ ,  $M_{1\text{-back}}$  and  $R_{\text{semantic}}$ ,  $K_{\text{semantic}}$ ,  $M_{\text{semantic}}$ ), as well as all auditory stimuli in each task condition (Auditory<sub>control</sub>, Auditory<sub>1-back</sub>, and Auditory<sub>semantic</sub>), regardless of performance. Visual words for which a response was omitted were modeled as events of no interest, as were buffer items. An additional regressor modeled the 10-sec duration task cues. Also employed were six regressors per session modeling movement-related variance (three rigid-body translations and three rotations determined from the realignment stage) and a session-specific constant term modeling the mean over scans.

The time series in each voxel were high-pass-filtered to 1/128 Hz to remove low-frequency noise and scaled within-session to a grand mean of 100 across both voxels and scans. Parameter estimates for events of interest



**Figure 1.** Schematic representation of experimental design. Volunteers were scanned during the study phase, during which they made animacy decisions to visually presented words while concurrently performing one of three secondary tasks on auditorily presented words spoken by either a man or a woman. For the secondary tasks, volunteers indicated when a word was: spoken in the female voice (“control” task), spoken in the same voice as the previous word (“1-back” task), or represented an object most likely found outdoors (“semantic” task). Note that while each concurrent task condition was performed as a 4-min duration block, activity elicited by both study and secondary task items was modeled as a series of discrete events.

were estimated using a General Linear Model. Non-sphericity of the error covariance was accommodated by an AR(1) model, in which the temporal autocorrelation was estimated by pooling over suprathreshold voxels (Friston et al., 2002). The parameters for each covariate and the hyperparameters governing the error covariance were estimated using Restricted Maximum Likelihood (ReML). Effects of interest were tested using linear contrasts of the parameter estimates. These contrasts were carried forward to a second stage in which subjects were treated as a random effect. The peak voxels of clusters exhibiting reliable effects are reported in MNI coordinates. In unmasked contrasts (see below), only those effects surviving an uncorrected threshold of  $p < .001$  and including four or more contiguous voxels are reported. Cortical effects were surface rendered onto the PALS-B12 atlas using the Caret software package (<http://brainmap.wustl.edu/caret>; Van Essen, 2005).

Regions of overlap between the outcomes of two contrasts were identified by inclusively masking the relevant SPMs. When the two contrasts were independent, the statistical significance of the resulting SPM was computed using Fisher's method of estimating the conjoint significance of independent tests (Lazar, Luna, Sweeney, & Eddy, 2002; Fisher, 1950). Exclusive masking was used to identify voxels where effects were not shared between two contrasts. Note that the more liberal the threshold of an exclusive mask, the more conservative is the masking procedure.

## RESULTS

### Behavioral Performance

The degrees of freedom for analyses described below involving factors with more than two levels were adjusted for nonsphericity using a Greenhouse–Geisser correction (Greenhouse & Geisser, 1959).

#### Study Phase

Accuracy and response times (RTs) for items studied under each of the divided-attention conditions are given in Table 1. Relative to the control condition, accuracy of animacy classifications in the 1-back condition did not differ [ $t(14) < 1$ ], but was significantly worse in the semantic condition [ $t(14) = 2.40, p < .05$ ]. To assess whether this accuracy difference varied according to later memory, analysis of variance (ANOVA) with factors of memory (R vs. K vs. M) and task (control vs. semantic) was performed. There was no interaction between memory and task ( $F < 1$ ).

To determine whether the type of secondary task influenced latency to respond to study items, ANOVA was performed on RTs to study items as a function of secondary task (control vs. semantic vs. 1-back). A main

**Table 1.** Accuracy and Response Times (Mean and Standard Deviation) for Items Studied under Each of the Divided-attention Conditions (Reported as a Function of Later Memory Performance and Collapsed across Later Memory)

	<i>Remember</i>	<i>Know</i>	<i>Miss</i>	<i>Across Memory</i>
<i>Accuracy</i>				
Control	0.85 (0.08)	0.87 (0.06)	0.83 (0.05)	0.84 (0.05)
1-Back	0.84 (0.07)	0.87 (0.09)	0.82 (0.08)	0.84 (0.06)
Semantic	0.81 (0.09)	0.82 (0.08)	0.81 (0.07)	0.81 (0.06)
<i>Response Times</i>				
Control	971 (109)	962 (152)	1017 (168)	983 (136)
1-Back	1032 (172)	1025 (128)	1059 (174)	1038 (150)
Semantic	1165 (129)	1123 (164)	1164 (184)	1151 (145)

effect of task [ $F(1.78, 24.96) = 48.05, p < .0001$ ] was further interrogated by pairwise  $t$  tests, which revealed slower animacy decisions in the 1-back condition than in the control condition [ $t(14) = 3.91, p < .005$ ], and even slower decisions in the semantic condition [1-back vs. semantic:  $t(14) = 5.78, p < .0001$ ].

To assess whether these differences in RTs were predictive of later memory performance, ANOVAs were performed on RTs to study items conditionalized on later memory performance [with factors of memory (R vs. K vs. M) and task (control vs. semantic vs. 1-back)]. A main effect of memory [ $F(1.54, 21.63) = 4.33, p < .05$ ] was driven by faster animacy judgments across tasks to study items later accorded a know response relative to those items incorrectly judged new ["misses,"  $t(14) = 2.63, p < .02$ ]. However, as is noted below, the fMRI subsequent memory effects we report are confined to items associated with recollection (remember vs. miss), and no differences in RTs were found between study judgments in these two classes of study item ( $p > .1$ ). Additionally, as in the case of accuracy, there was no Task by Memory interaction ( $F < 1$ ). Thus, although overall accuracy was affected by concurrently performing the semantic secondary task, and overall RTs were influenced by both the 1-back and the semantic tasks, neither measure varied as a function of later memory. Therefore, the differences in fMRI subsequent memory effects due to secondary task that are reported below are not confounded with differential study performance for recollected versus forgotten items.

#### Recognition Memory

Recognition memory performance is summarized in Table 2. Recollection was estimated as the probability of

endorsing an old item as remembered minus the probability of a remember response for new items ( $pR = pR_{old} - pR_{new}$ ). Relative to items studied under the control condition, recollection was significantly and equivalently worse for items studied under the two other divided-attention conditions [ $pR_{control} = .29$ ,  $SD = .11$ ;  $pR_{1-back} = .24$ ,  $SD = .12$ ;  $pR_{semantic} = .24$ ,  $SD = .13$ ; control vs. 1-back:  $t(14) = 2.63$ ,  $p < .01$ ; control vs. semantic:  $t(14) = 2.80$ ,  $p < .01$ ]. Familiarity was estimated as the probability an old item was accorded a K response given it was not accorded an R response, minus the corrected K probability for new items [ $pF = (pK_{old}/1 - pR_{old}) - (pK_{new}/1 - pR_{new})$ ] (Yonelinas & Jacoby, 1995). In contrast to recollection, familiarity was not affected by either the 1-back or semantic secondary tasks [ $pF_{control} = .17$ ,  $SD = .10$ ;  $pF_{1-back} = .17$ ,  $SD = .08$ ;  $pF_{semantic} = .14$ ,  $SD = .08$ ; control vs. 1-back:  $t(14) < 1$ ; control vs. semantic:  $t(14) = 1.13$ ,  $p > .1$ ].

## fMRI Findings

Because the experimental manipulations impaired recollection but not familiarity, analyses of fMRI subsequent memory effects are confined to those associated with recollection (R vs. M). We first identified regions that exhibited subsequent memory effects separately for the three conditions, and determined whether any effects were shared between tasks. We then determined whether subsequent memory effects in the control condition were attenuated by either or both of the other two divided-attention conditions. The final set of analyses sought to determine whether the task “tradeoff” effects observed in Uncapher and Rugg (2005a) (see Introduction) between the control and the 1-back conditions were also evident in the present study.

### Subsequent Memory Effects

**Control task.** As illustrated in Figure 2 and listed in Table 3a, several regions demonstrated significant ( $p <$

.001) subsequent memory effects in the control condition. These regions included the left posterior hippocampus and the dorsal aspect of the left IFG. Analysis of parameter estimates for the peak voxel of each cluster revealed that none of these voxels showed subsequent memory effects in the 1-back or the semantic condition (all  $ps > .1$ ).

**1-Back task.** Regions exhibiting subsequent memory effects in the 1-back task are shown in Figure 2 and reported in Table 3b. Three regions demonstrated significant effects, including bilateral regions of the ventral IFG. Analysis of parameter estimates revealed that there were no significant subsequent memory effects in either of the other two conditions in any of these regions (all  $ps > .09$ ).

**Semantic task.** Only one region—the left ventral IFG—exhibited a subsequent memory effect in the semantic condition (see Figure 2 and Table 3c). This region did not overlap with the cluster identified in the 1-back subsequent memory contrast and did not show significant effects in the control or 1-back conditions ( $ps > .1$ ).

As reported above, no regions that demonstrated a significant ( $p < .001$ ) subsequent memory effect in one condition also exhibited significant effects in either of the other two conditions ( $ps$  in all other conditions  $> .09$ ). To reduce the probability of Type II error in determining whether any voxels exhibited common effects, we created three separate pairwise inclusive masks, with each contrast thresholded at  $p < .01$  (to give a conjoint threshold of  $p < .001$  for each pair of contrasts). We inclusively masked the subsequent memory contrasts for the following conditions: (i) control with 1-back, (ii) control with semantic, and (iii) 1-back with semantic. No suprathreshold voxels were identified in any of these masks. Thus, we were unable to find regions where subsequent memory effects were shared between any pair of conditions.

### Attenuation of Subsequent Memory Effects

As outlined in the Introduction, a key aim of the present study was to test the prediction that the subsequent memory effects evident in the control condition would be attenuated in the semantic condition, but not in the 1-back condition. Whereas the analyses reported above revealed that no regions demonstrated overlapping subsequent memory effects across conditions, they do not license the conclusion that effects differ significantly in magnitude across conditions. It is entirely possible for effects to be suprathreshold in one condition and subthreshold in another without differing significantly. Thus, the following analyses searched for regions where, relative to the control condition, subsequent memory

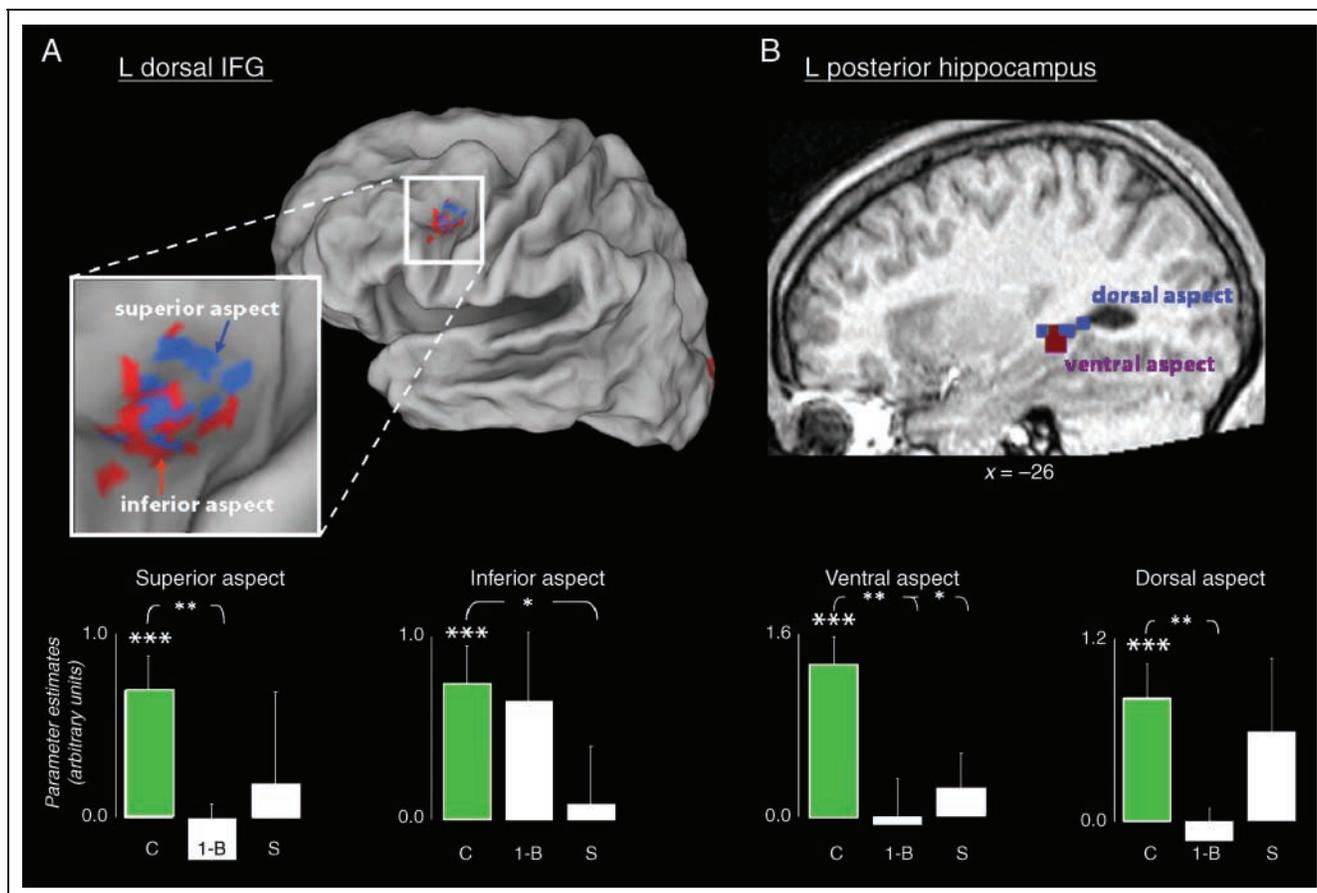
**Table 2.** Recognition Memory Performance (Mean and Standard Deviation) for Items Studied under Each of the Divided-attention Conditions

Old Items	Remember	Know	Miss
Control	0.36 (0.12)	0.27 (0.09)	0.25 (0.08)
1-Back	0.31 (0.13)	0.28 (0.10)	0.28 (0.11)
Semantic	0.31 (0.14)	0.27 (0.10)	0.28 (0.11)
New Items	Remember False Alarm	Know False Alarm	Correct Rejection
	0.07 (0.03)	0.23 (0.11)	0.70 (0.13)



**Table 3.** Regions Exhibiting Subsequent Memory Effects in the Control, 1-Back, and Semantic Conditions

Location ( $x, y, z$ )	Peak Z (No. of Voxels)	Region	Approx. BA
<i>(a) Control Condition</i>			
-39 12 30	3.48 (9)	L dorsal inferior frontal gyrus	9/44
-30 -30 -3	3.98 (45)	L posterior hippocampus	
36 -75 45	4.01 (5)	R superior parietal	7
39 -87 3	3.64 (9)	R middle occipital gyrus	19
-9 -102 3	4.17 (11)	L cuneus	18
<i>(b) 1-Back Condition</i>			
-21 27 -21	3.50 (7)	L ventral inferior frontal gyrus	11
21 33 -9	3.43 (5)	R ventral inferior frontal gyrus	47
63 -30 6	3.46 (6)	R superior temporal gyrus	42
<i>(c) Semantic Condition</i>			
-33 24 -21	3.39 (4)	L ventral inferior frontal gyrus	47



**Figure 3.** Attenuations of control task subsequent memory effects. Regions in (A) the left dorsal inferior frontal gyrus (IFG) and (B) the left posterior hippocampus, which exhibited significant ( $p < .001$ ) subsequent memory effects in the control condition, were differentially attenuated by the harder concurrent task (1-back or semantic) conditions. Effects are displayed on a standardized brain. Graphs display mean parameter estimates (and standard errors) from the peak voxel of the illustrated cluster.  $***p < .001$ ,  $**p < .01$ ,  $*p < .02$ . C = control condition; 1-B = 1-back condition; S = semantic condition.

**Table 4.** Subsequent Memory Effects That Are Attenuated by the 1-Back Condition, the Semantic Condition, or Both

	<i>Location (x, y, z)</i>	<i>Peak Z (No. of Voxels)</i>	<i>Region</i>	<i>Approx. BA</i>
<i>Attenuated by:</i>				
(a) 1-back only	–33 3 30	2.91 (5)	L dorsal inferior frontal gyrus	9/44
	–21 –42 3	2.75 (12)	L posterior hippocampus	
(b) Semantic only	–42 12 27	2.16 (4)	L dorsal inferior frontal gyrus	9/44
	–12 –102 3	2.37 (10)	L inferior occipital lobe	18
(c) Both conditions <sup>a</sup>	39 –87 0	3.63 (6)	R middle occipital gyrus	19
	42 –87 0	3.12		
	–30 –30 –3	3.98 (14)	L posterior hippocampus	
	–30 –30 –3	2.23		

Z values refer to the significance of the specified interaction [i.e., 1-back only:  $(R_{\text{control}} > M_{\text{control}}) \times (R_{1\text{-back}} > M_{1\text{-back}})$ ; Semantic only:  $(R_{\text{control}} > M_{\text{control}}) \times (R_{\text{semantic}} > M_{\text{semantic}})$ ; Both conditions:  $(R_{\text{control}} > M_{\text{control}}) \times (R_{1\text{-back, semantic}} > M_{1\text{-back, semantic}})$ ].

<sup>a</sup>Top values refer to peak voxel of clusters in 1-back condition, bottom values to semantic condition.

### *Subsequent memory effects attenuated in both tasks.*

To identify regions where subsequent memory effects in the control condition were attenuated in both the 1-back and the semantic conditions, the subsequent memory contrast for the control condition (thresholded at  $p < .001$ ) was inclusively masked with both interaction contrasts (each thresholded at  $p < .05$ ). Figure 3 illustrates and Table 4c lists the regions identified by this procedure. These regions included the left posterior hippocampus and right middle occipital gyrus. As is evident from the figure, the hippocampal cluster was adjacent to the anterior edge of the cluster where subsequent memory effects were selectively attenuated in the 1-back condition.

### *Task Effects*

For the reasons outlined in the Introduction, we were interested in determining whether the pattern of task “tradeoff” effects between the activity elicited by study and secondary task items evident in Uncapher and Rugg (2005a) was also observed in the present study. We therefore defined four regions of interest (ROIs), each a sphere of radius 8 mm, centered on the coordinates derived from the regions of dorsolateral prefrontal (DLPFC) and lateral parietal cortices demonstrating task tradeoff effects in Uncapher and Rugg (2005a). The coordinates were (56, 9, 38) and (–56, 9, 38) for the right and left DLPFC and (45, –38, 47) and (–42, –45, 44) for the right and left lateral parietal cortex, respectively. Mean parameter estimates were computed across all voxels within each ROI.

Pairwise *t* tests on these parameter estimates revealed that study item activity was significantly reduced in the 1-back relative to the control task in all four ROIs (all  $p$ s  $< .01$ ;  $p < .0003$  when collapsed across region; Fig-

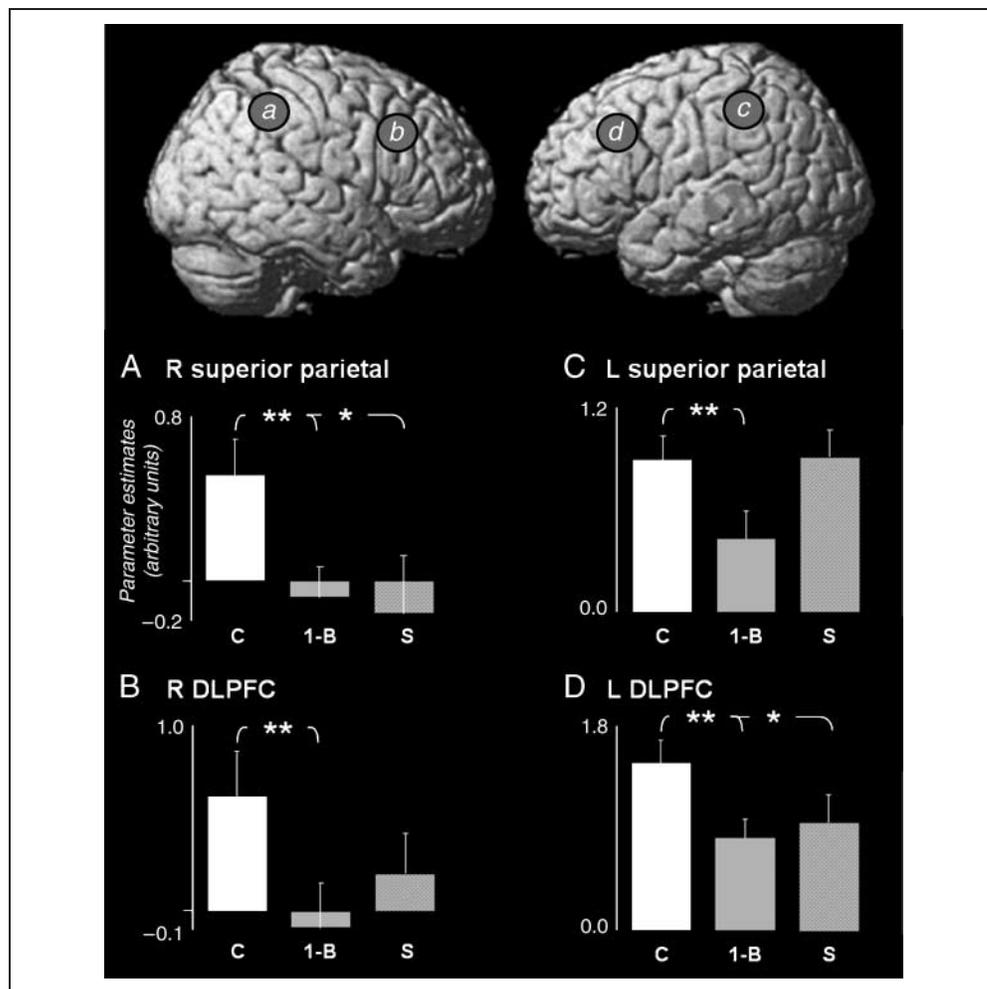
ure 4). [Although not directly relevant to the question at hand, study item activity in the semantic task was reduced relative to the control task in two of the regions, the left DLPFC and the right lateral parietal cortex ( $p < .05$  and  $.02$ , respectively).] By contrast, there were no detectable differences in auditory item activity in any of the ROIs. Thus, only one side of the previously reported tradeoff effects was observed in the present study, specifically, less activity was elicited by study items in the 1-back compared to the control condition.

## DISCUSSION

### Behavioral Performance

Study performance was less accurate and slower during concurrent performance of the semantic secondary task relative to the control task. By contrast, accuracy on the study task was comparable between the 1-back and the control conditions, although responses were slower in the 1-back condition. Thus, both the semantic and the 1-back secondary tasks competed with the study task for processing resources to a greater extent than did the control task, albeit perhaps in different ways. This competition for resources detracted from the efficacy with which study items could be encoded; relative to items studied concurrently with the control task, fewer items studied under either the 1-back or the semantic conditions were later given a “remember” response. Indeed, these two divided-attention tasks decreased estimates of later recollection by an equivalent amount. Importantly, no behavioral subsequent memory effects were observed. In other words, in no condition were RTs or accuracy significantly different for study items later recollected relative to those later forgotten. Thus, the interactions between secondary task and fMRI subsequent memory effects discussed below are not confounded by

**Figure 4.** Effects of secondary task on study item activity in ROIs. Activity elicited by study items in regions held to support executive processing [right and left superior parietal cortex (A and C, respectively) and dorsolateral prefrontal cortex (B and D, respectively)] was consistently attenuated during concurrent performance of the 1-back task relative to the control task (all  $p$ s < .01). Graphs display mean parameter estimates (and standard errors) from the spherical ROIs. \*\* $p$  < .01, \* $p$  < .05. C = control condition; 1-B = 1-back condition; S = semantic condition.



differential study performance for recollected versus forgotten items.

In contrast to recollection, we did not observe significant divided-attention effects on estimates of familiarity. This result is consistent with the general finding that divided attention at study is more detrimental to later recollection than later familiarity. Indeed, although in many studies estimates of recollection and familiarity are both reduced when attention is divided at study (see Yonelinas, 2002 for review), in some cases (as in the present study), there is no detectable effect on familiarity (Yonelinas, 2001; Jacoby & Kelley, 1992). As noted in the Results, the failure of the divided-attention manipulations to influence estimates of familiarity motivated us to confine fMRI analyses to subsequent memory effects associated with recollection.

The finding that later recollection was impaired when attention was shared with either the semantic or the 1-back task during encoding is consistent with a large behavioral literature (see Introduction). The present study extends these behavioral findings by investigating the neural correlates of the effects of divided attention on later recollection, rather than on undifferentiated recognition memory (see Uncapher & Rugg, 2005a; Kensinger et al.,

2003). To our knowledge, this is the first study to do so (though see Mangels, Picton, & Craik, 2001 for a relevant ERP study). Additionally, as the two critical secondary tasks had an equivalent impact on later recollection, it was possible to address the question of whether successful episodic encoding depends on a common attentional resource, or on multiple resources.

### fMRI Findings

The present study yielded two novel findings. First, secondary tasks that compete with a study task for different kinds of attentional resource have dissociable effects on the neural correlates of successful episodic encoding, and thus, presumably, on the cognitive operations supporting encoding. Second, diversion of these resources away from the study task is associated with recruitment of alternate encoding processes. These processes appear to partially compensate for the disruption to processes that support encoding in the control condition, when attention is relatively undivided.

We turn first to parallels between the present and previous studies. Echoing previous findings (Uncapher

& Rugg, 2005a; Kensinger et al., 2003), subsequent memory effects were evident in the control condition in the left IFG and in the left hippocampus. Because these regions have been consistently identified when the study task was fully attended (see Introduction), the effects in the present control condition likely parallel those observed under full attention. In both regions, effects were attenuated when volunteers concurrently performed either the 1-back or the semantic secondary task. As is discussed below, this finding parallels that of Kensinger et al. (2003), but is counter to our previous study (Uncapher & Rugg, 2005a).

The region in the left IFG that demonstrated subsequent memory effects in the control condition was in the dorsal aspect of the gyrus, in the vicinity of BA 44. As noted above, this region has consistently been found to demonstrate subsequent memory effects when attention was undivided. The region has also been implicated in controlled semantic and phonological processing (for review, see Costafreda et al., 2006). It is dorsal to a region of BA 47/45, which also demonstrates subsequent memory effects in many studies (e.g., de Zubicaray, McMahon, Eastburn, Finnigan, & Humphreys, 2005; Uncapher & Rugg, 2005b; Chee, Goh, Lim, Graham, & Lee, 2004; Fletcher, Stephenson, Carpenter, Donovan, & Bullmore, 2003; Otten et al., 2001; Henson et al., 1999; Wagner et al., 1998), and which appears to be more specifically involved in semantic processing (e.g., Wagner, Pare-Blagoev, Clark, & Poldrack, 2001; Poldrack et al., 1999; but see Gold & Buckner, 2002). Along with others (e.g., Brassens et al., 2006; Fletcher et al., 2003; Buckner, Wheeler, & Sheridan, 2001; Wagner et al., 1998), we interpret these effects in the IFG in terms of the benefits accruing to later memory for words whose semantic (and, perhaps, phonological) attributes receive relatively greater emphasis during study processing. The attenuation of dorsal subsequent memory effects under the divided-attention conditions of the present study presumably is a consequence of the increased demands under these conditions on the processes supported by this region.

The finding that the 1-back and semantic tasks attenuated subsequent memory effects in adjacent, but seemingly distinct, dorsal IFG loci raises the possibility of functional heterogeneity within the IFG on a more fine-grained spatial scale than that accommodated by the “dorsal–ventral” distinction noted above. This broader distinction is relevant, however, to our finding that, for both of the divided-attention conditions, attenuation of dorsal IFG subsequent memory effects was accompanied by the emergence of effects in distinct ventral IFG regions. In light of evidence that the ventral IFG (albeit, somewhat lateral to the regions identified here) may be particularly important for “controlled semantic retrieval” (Wagner et al., 2001), it is tempting to speculate that the ventral subsequent memory effects observed in the present study reflect increased reliance of attentionally mediated recovery of word meaning under dual-task

conditions. As with the dorsal IFG, the finding that the 1-back and semantic tasks were associated with anatomically distinct ventral effects is suggestive of functional heterogeneity on a relatively fine-grained spatial scale.

Turning to the hippocampus, it has been proposed that subsequent memory effects in this structure reflect its role in the encoding of patterns of cortical activity elicited during the on-line processing of an episode (Otten et al., 2001; for a similar view, see Wagner et al., 1998). In the present study, a subsequent memory effect in the left posterior hippocampus was evident in the control condition. As in the case of the left dorsal IFG, the hippocampal effect was attenuated when secondary task load increased. Whereas the entire hippocampal cluster showed attenuated activity during the 1-back condition, only the more ventral aspect of the cluster was attenuated in the semantic condition. This single dissociation may reflect functional heterogeneity in the hippocampus, but the possibility of a Type II error cannot be dismissed. Regardless, the finding that hippocampal subsequent memory effects were attenuated under divided attention raises the possibility that cortical input to the hippocampus was reduced under these conditions.

As already noted, the present finding of an attenuation of left IFG and hippocampal subsequent memory effects in the 1-back and semantic conditions is consistent with the results of Kensinger et al. (2003), but contrary to those of Uncapher and Rugg (2005a). This is somewhat surprising given the similarity of the present 1-back and control conditions to the secondary task manipulations employed in our previous study. A possible explanation for this divergence lies in the nature of the secondary task items in the two studies. In Uncapher and Rugg, the items consisted of repeated presentations of the digits 1 through 10, whereas in the present study, secondary task items were trial-unique nouns. It is possible that even in the 1-back task, when the meaning of the words was irrelevant, their novelty led to obligatory semantic processing, and thus, to competition for semantic processing resources with the study task. Thus, unlike in our original study, the 1-back task may have competed with the study task for both task-specific as well as task-generic resources.

A key finding in our previous divided-attention study was the “tradeoff” effects between the study and secondary tasks: As secondary task load increased, there was an attenuation of study item activity and a concomitant enhancement of secondary item activity in regions associated with executive control (left and right dorso-lateral prefrontal and superior parietal cortex). In the present study, we found a strikingly similar pattern of effects for the study items: In all four regions exhibiting tradeoff effects in the previous experiment, study item activity was of lower magnitude in the 1-back than in the control condition. In line with our previous interpretation, we assume that the task-related reduction in study item activity in these regions reflects a reduction in the

neural resources allocated to the processing of study items. To the extent that this assumption is correct, the present findings substantially strengthen the proposal that one factor mediating the detrimental effects of divided attention on encoding is a reduction in the generic processing resources available to support study processing (Uncapher & Rugg, 2005a; Fernandes & Moscovitch, 2000).

Unlike in our prior study, the activity elicited by secondary task items was not significantly enhanced in the 1-back relative to the control condition. There are several design differences that may account for the discrepancy between the present and previous studies. These include the employment of trial-unique words versus repeated digits, the different task demands (voice vs. digit classification), and a longer SOA (and concomitantly, almost a halving of the number of auditory items) in the present compared with the previous study. Together, these factors likely led to a relative reduction in the present study in sensitivity to detect task-related modulation of auditory item activity.<sup>3</sup> Whatever the reason for the failure to observe such a modulation, this null result does not detract from the significance of our findings with respect to the study items.

Unlike in the studies of Uncapher and Rugg (2005a) and Kensinger et al. (2003), the harder divided-attention manipulations in the present study were associated with the emergence of subsequent memory effects that were not evident in the control condition. In neither of these prior studies, however, were subsequent memory effects segregated according to later recollection, raising the possibility that additional effects associated with harder divided attention were diluted by the inclusion of items later recognized on the basis of familiarity alone. In the present study, the shift in the loci of subsequent memory effects according to secondary task condition (from the left dorsal to left ventral IFG) might reflect a reallocation of processing resources supporting effective encoding. An unresolved issue is whether this shift was associated with a corresponding shift in what was recollected.<sup>4</sup> That is, did the content of recollection differ either in kind or in degree for items studied under the harder divided-attention conditions relative to the control condition? The memory test employed here did not allow us to address this issue directly. However, in light of prior evidence that differences in the nature of the information recollected on a later memory test are associated with regionally distinct subsequent memory effects (Uncapher et al., 2006), the possibility that recollective content differs according to secondary task deserves further investigation.

Together with previous results, our findings indicate that the precise relation between attention and encoding remains to be fully delineated; the three studies that have investigated the effects of divided attention on fMRI subsequent memory effects have yielded three different patterns of results. Kensinger et al. (2003) re-

ported that divided attention was associated with a quantitative reduction in the magnitude of subsequent memory effects in the left IFG and left hippocampus; Uncapher and Rugg (2005a) found no difference in the magnitude of subsequent memory effects in these two regions; and in the present study, attenuation of subsequent memory effects in the two regions was associated with the emergence of additional effects in other prefrontal regions. Thus, there may be no single mechanism by which divided attention interferes with memory encoding (see also Naveh-Benjamin, 2006).

That said, what general conclusions might be drawn regarding the nature of the relationship between divided attention and encoding? First, findings of attenuated subsequent memory effects (Kensinger et al., 2003 and the present study) suggest that divided attention can impact encoding by reducing the availability of resources supporting study processing. Second, the shift in the loci of subsequent memory effects observed in the present study suggests that divided attention can influence the nature of the processing engaged in service of the study task, and that this might have detrimental effects on encoding. Finally, the present findings of attenuated dorsolateral and superior parietal study item activity in the 1-back condition, along with the findings of Uncapher and Rugg (2005a), suggest that divided attention can also impact later memory by reducing the availability of generic processing resources. The effects of divided attention on memory encoding seem therefore to reflect the detrimental consequences of resource limitations at both task-generic and task-specific levels. The mechanism by which divided attention impacts later memory depends on the precise interplay between the processing demands of the study and secondary tasks.

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## Notes

1. An anonymous reviewer noted that the study task strategies adopted by the excluded and included subjects may have differed, leading to the possibility that the findings do not generalize to the entire population from which our sample was drawn.

2. Because these two contrasts are nonorthogonal, their joint significance is simply the stricter of the two thresholds (i.e.,  $p < .001$ ). The procedure amounts to a planned, voxel-wise interrogation of a functionally defined region of interest, within which all voxels demonstrate a subsequent memory effect at our pre-experimentally defined threshold. Note that the interaction contrast on its own would not suffice; although

the interaction identifies regions affected by the divided attention manipulation, it does not speak to whether the affected regions also demonstrate reliable subsequent memory effects in the control condition.

3. Although auditory item activity did not significantly differ between the control and the harder divided attention conditions, there was a numerical trend for an enhancement in the predicted direction (greater activity in the 1-back than in the control condition).

4. We thank an anonymous reviewer for drawing our attention to this possibility.

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