

The Role of the Prefrontal Cortex in Recognition Memory and Memory for Source: An fMRI Study

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We employed fMRI to index neural activity in prefrontal cortex during tests of recognition and source memory. At study, subjects were presented with words displayed either to the left or right of fixation, and, depending on the side, performed one of two orienting tasks. The test phase consisted of a sequence of three 10-word blocks, displayed in central vision. For one block, subjects performed recognition judgements on a mixture of two old and eight new words (low density recognition). For another block, recognition judgements were performed on a mixture of eight old and two new words (high density recognition). In the remaining block, also consisting of eight old and two new items, the requirement was to judge whether each word had been presented at study on the left or the right. Relative to the low density condition, high density recognition was associated with increased activity in right and, to a lesser extent, left, anterior prefrontal cortex (BA 10), replicating the findings of two previous PET studies. Right anterior prefrontal activity did not show any further increase during the source task. Instead, greater activity was found, relative to high density recognition, in left BA 10, left inferior frontal gyrus (BA 45/47), and bilateral opercular cortices (BA 45/47). The findings are inconsistent with the proposal that activation of right anterior prefrontal cortex during memory retrieval reflects “postretrieval” processing demands, such demands being considerably greater for judgments of source than recognition. The findings provide further evidence that the left prefrontal cortex plays a role in episodic memory retrieval when the task explicitly requires recovery of contextual as well as item information.

INTRODUCTION

A consistent finding in functional neuroimaging studies of memory is that performance of episodic retrieval tasks is associated with activation (relative to a range of control tasks) of right prefrontal cortex (see Buckner

and Koutstall, 1998, and Fletcher *et al.*, 1997, for reviews). The extent of this activation, and the specific regions involved, vary across studies, but commonly include anterior lateral cortex in the vicinity of Brodmann area (BA) 10 and dorsolateral cortex of the middle frontal gyrus (BA 46/9). The functional significance of these findings has been the subject of much debate. They have for example been interpreted as reflecting the adoption of a “retrieval mode” (Nyberg *et al.*, 1995), the expenditure of “retrieval effort” (Schacter *et al.*, 1996), and the engagement of “postretrieval” processing (Rugg *et al.*, 1996).

According to the postretrieval hypothesis, right prefrontal activation reflects demands placed upon cognitive operations responsible for acting on the products of memory retrieval. These operations are thought to support such processes as the integration of retrieved information into a coherent episodic representation, and the monitoring of retrieved information for its relevance to task-related behavioral goals. Support for the postretrieval hypothesis comes from three sources. First, neuropsychological evidence suggests that the foregoing processes are indeed likely to depend upon the prefrontal cortex (Shallice, 1988). Second, the hypothesis leads to the prediction that right prefrontal activity should be greater when retrieval is successful—and hence yields information for postretrieval processes to operate on—than when retrieval is unsuccessful. This prediction has been confirmed in three studies of recognition memory in which the probability that a test word elicits successful retrieval was manipulated (Buckner *et al.*, 1998; Rugg *et al.*, 1996, 1998a; but see Kapur *et al.*, 1995 and Nyberg *et al.*, 1995 for failures to find this effect, and Wagner *et al.*, 1998 for evidence that the effect is modulated by retrieval strategy).

The third source of evidence supporting the postretrieval hypothesis of right prefrontal function comes from the findings of event-related potential (ERP) studies of episodic memory retrieval. In a number of studies (see Allan *et al.*, 1998 and Rugg and

Allan, in press, for reviews), ERPs to test items eliciting successful retrieval were found to exhibit, relative to ERPs to new items, a late-onsetting, sustained positive-going shift, which was maximal over right frontal scalp. While it is not possible to prove that this memory-related ERP effect reflects neural activity in the right prefrontal cortex, its scalp distribution, together with the aforementioned functional neuroimaging findings implicating this region in episodic retrieval tasks, make this a highly plausible hypothesis. On the assumption that the hypothesis is correct, the existence of the “right frontal old/new effect”—reflecting as it does neural activity sensitive to whether a retrieval cue elicits successful or unsuccessful retrieval—gives further credence to the postretrieval hypothesis outlined above.

Wilding and Rugg (1996) reported that the right frontal ERP effect was larger for recognized test items that attracted correct source memory judgements than it was for items attracting incorrect judgements. On the basis of this finding, they proposed (see also Donaldson and Rugg, 1998) that the level of engagement of the postretrieval processes reflected by the effect varies according to the amount of episodic information retrieved. Since the right frontal old/new effect appears to be more prominent in tests (such as source memory) which require access to specific details of the encoding episode than in tests of simple recognition memory, it has further been proposed (Allan *et al.*, 1998; Donaldson and Rugg, 1998) that the processes reflected by the effect are engaged in a task-dependent manner. Specifically, it was proposed that these processes will be engaged to a greater extent as the demands placed upon postretrieval processes increase. These demands are relatively light for yes/no recognition memory, when a response can be selected on the basis of a superficial evaluation of retrieval products, but are considerable for tasks such as source memory, when retrieved information must be evaluated more fully before a response can be selected.

On the assumption that the right frontal ERP effect can indeed be identified with the retrieval-related right prefrontal activity identified in functional neuroimaging studies, the theoretical framework developed to account for the ERP findings (Allan *et al.*, 1998; Rugg *et al.*, 1998b; Wilding and Rugg, 1996) leads to a clear prediction: previously studied items should give rise to more right prefrontal activity when presented in the context of a source memory task than when they are subjected to simple recognition judgments. The present experiment tests this hypothesis.

The experiment also permits a very different view of the role of the prefrontal cortex in episodic memory retrieval to be assessed. Nolde *et al.* (1998a) noted that although authors have emphasized the role of the right prefrontal cortex in episodic memory retrieval when discussing functional neuroimaging findings, it is not

uncommon for such findings also to include retrieval-related activation in *left* prefrontal cortex. According to Nolde *et al.* (1998a), whether or not left prefrontal activation is observed is systematically related to the “reflective demands” of the retrieval task. When these demands are low, as in two-alternative, forced choice recognition, only right prefrontal cortex is engaged. When reflective demands are high, however, as is the case in tasks requiring the evaluation of episodic detail, the left prefrontal cortex also is engaged. Using event-related fMRI, Nolde *et al.* (1998b) reported findings consistent with this hypothesis. In three of four subjects studied they found that regions of left lateral prefrontal cortex (in the vicinity of BAs 10 and 46) showed greater signal intensity when test items were subjected to source judgments rather than judgments of recognition memory. By contrast, no region of the right prefrontal cortex discriminated between the two tasks. These findings are inconsistent with the prediction, discussed above, that it is the right prefrontal cortex in which activity should vary according to the demands of the retrieval task.

Similar findings were reported by Henson *et al.* (1999). The key contrast in this study was between trial blocks in which items were subjected to simple old/new recognition judgments and blocks in which items from only one of the two study contexts (e.g., items appearing at study on the top half of the display monitor) were to be accorded an “old” judgment, thereby forcing subjects to determine the source of each old item. As in Nolde *et al.* (1998b), source judgments were associated with greater activity in left prefrontal cortex (BA 46). Unlike the findings from Nolde *et al.*, however, greater activity was also observed in a restricted region of right prefrontal cortex (BA 46), a finding to some extent consistent with the prediction derived from the ERP findings discussed above.

In the present study we employed fMRI to contrast the neural activity in prefrontal cortex under three different retrieval conditions. Two of these conditions required recognition memory judgments, in one case on trial blocks composed mainly of new items (low density recognition), and in the other, on blocks consisting largely of studied (old) items (high density recognition). The third retrieval condition also employed trial blocks containing mainly old items, but with the requirement to perform a source rather than a recognition judgment. By contrasting the two recognition memory conditions, it was possible to identify prefrontal regions sensitive to the probability of retrieval success; regions engaged, according to the postretrieval hypothesis, as a consequence of the need to process the products of memory retrieval. It was expected that these regions would be predominantly right-lateralized. By contrasting the source task with the high density recognition condition, it was possible to address two key questions:

first, whether activity in right prefrontal regions that is sensitive to retrieval success is greater when source rather than recognition judgments are required, as predicted by ERP findings; and second, whether the source task engaged regions of left prefrontal cortex to a greater extent than does recognition memory, as predicted by the hypothesis of Nolde *et al.* (1998a).

METHOD

Subjects

Subjects were six healthy right-handed adults, 3 male and 3 female. Mean age was 29 years (range 23–38).

Experimental Stimuli and Presentation

The stimuli consisted of a pool of 186 low-to-medium frequency words. One hundred and fourteen of these words were selected at random and used to form 6 study lists, each of 19 items (the first of which acted as a filler). Each study list was paired with a corresponding 30 item test list. Eighteen of the test items were members of the study list (old items), whereas the remainder did not appear on any of the study lists (new items). The test lists were organized into three blocks of 10 items. Two of these blocks comprised a random assortment of eight old words and two new words (high density blocks), while the remaining block was made up of two old words and eight new ones (low density block). Three versions of each test list were created, such that the block containing a majority of new items was situated at the beginning, the middle, or the end of the list. A seventh study/test list combination was also constructed and employed for practice.

Stimulus Presentation Parameters

Stimuli were presented using a computer-controlled video projector focused on a mirror fixed to the MR head coil. During the study phase a fixation cross was continuously present at the center of the screen, and items were displayed with their center letters displaced by approximately 15° left or right of fixation. The side of presentation of each item was randomly determined. Presentation was subject paced, each item remaining on the screen until the subject had made the appropriate orienting task judgment (see below).

Test items were presented in central vision (replacing the fixation character) every 3.8 s for a duration of 500 ms. The first item of each test list was preceded by a 25.2-s period during which the screen was blank other than for the fixation character. The fixation character was then replaced for 7 s by a display (“O/N” or “L/R”) that served to remind the subject of the task required for the forthcoming block. This display was then replaced for a further 1.4 s by the fixation character, after

which the first item was presented. An identically structured interval intervened between the first and the second and the second and the third of the 10-item blocks comprising each test list.

Procedure

The study proper consisted of six study-test cycles, which were preceded by a practice cycle, during which fMRI data were not collected. The procedure for each cycle was identical. At study, instructions were to view each item in turn and to perform one of two orienting tasks depending on whether the item was displayed on the left or the right side of the screen. The relationship between side and task was counterbalanced across subjects. The two tasks were judgments of animacy (animate/inanimate) or pleasantness (pleasant/unpleasant). Subjects signalled their judgments verbally.

The test phase began approximately 3 min after study, during which time subjects were required to count back in threes from an arbitrary number to prevent rehearsal. Subjects were instructed that for each block of 10 items they should make either a recognition or a source judgment on each item, signalling their responses by depressing a button with the index or middle finger of their right hand. The mapping of response to finger was counterbalanced across subjects. For the recognition task, the instructions were to discriminate between studied (old) and unstudied (new) words. The instructions in the source task were to discriminate between items presented on the left and right side of the monitor during the study phase. Subjects were advised that their performance in this task would be helped by recalling the encoding task that had been carried out with each word, but that they should guess if necessary. Recognition judgments were required for both high and low density lists, whereas the source judgments were undertaken only with high density lists. In each test list, therefore, two blocks (one low density and one high density) were employed for recognition, and the remaining high density block was used for source judgments. Subjects were informed about the order in which the tasks were to be performed before the start of each test phase and were reminded about the upcoming task just before the onset of each block (see previous section). For each subject, the order of administration of the three conditions (high density recognition, low density recognition, and source) was different for each of the six study-test cycles. Across subjects, a different assignment of study/test lists to each of the six possible orderings of conditions was employed, and the sequence in which these orderings were administered was also varied.

fMRI Data Acquisition

A Siemens VISION MR scanner operating at 2 Tesla was employed to acquire both T1-weighted anatomical

images and gradient-echo, echo-planar T2*-weighted BOLD-sensitive images. Parameters for functional image acquisition were as follows: TE, 40 ms; TR, 4.8 s; slice thickness, 1.8 mm skip 1.2 mm; number of slices, 48; in-plane resolution, 3×3 mm. Slice orientation was axial, and the imaging volume was aligned to cover the whole brain. The image acquisition parameters were chosen in an effort to minimize drop-out in anterior frontal regions caused by magnetic susceptibility artefact while maintaining adequate sensitivity to task-related signal variation (Howseman *et al.*, 1999).

Functional data were acquired in six scanning runs. These were separated by the study phases of each study/test cycle, which lasted for approximately 6 min. Each run commenced with the acquisition of 6 dummy volumes, allowing tissue magnetization to achieve a steady state, after which 54 functional volumes were acquired. Thus, over the course of the experiment, a total of 324 functional images were obtained for each subject.

fMRI Data Analysis

The fMRI data were analyzed using SPM 97 (Wellcome Dept of Neurology, UK; <http://www.fil.ion.ucl.ac.uk/spm>). For each subject, a time-series consisting of all 324 images was formed, and the images were realigned and corrected for head movement. They were then stereotactically normalized, resampled, and transformed into the standard space of Talairach and Tournoux (1988). Each image was smoothed spatially with a gaussian kernel of 7 mm full-width half-maximum (FWHM), and the time-series was smoothed temporally with a 6-s FWHM kernel. Experimental contrasts were performed using the general linear model as implemented in SPM 97, with error terms estimated according to a fixed effects statistical model. For each subject, run was treated as a confounding variable, as were changes in signal at a frequency equal to or lower than 0.0032 Hz (thereby attenuating the effects of baseline drift across the imaging time series). Global changes in activity were removed by proportional scaling. The statistical reliability of between-condition contrasts was assessed using appropriately weighted box-car functions convolved with an idealized hemodynamic response function. Regions of prefrontal cortex were considered to exhibit a significant condition effect if they contained a cluster of 9 or more contiguous voxels significant at $P < 0.001$ (uncorrected for multiple comparisons).

RESULTS

Behavioral Performance

Because of technical failures, one block of functional data was lost from four subjects in the source task, and

from two subjects in each of the two recognition tasks. The behavioral data are reported averaged across the blocks on which functional data were acquired. Correct source judgments were made on a mean of 0.82 (SD = 0.07) of the trials containing an old word. This value differed significantly from the chance level of 0.5 [$t(5) = 21.15$, $P < 0.001$], indicating that subjects were well able to perform the task. Recognition accuracy was assessed by the sensitivity index $p(\text{Hit}) - p(\text{False Alarm})$. Mean accuracy was somewhat higher for low density than for high density blocks [0.91 (0.05) vs 0.78 (0.19)], but not to a statistically significant extent. The trend toward greater accuracy in the low density condition was carried largely by differences in the false alarm rates between the two conditions [0.05 (0.04) and 0.15 (0.16) for low and high density, respectively], rather than differences in hit rate [0.96 (0.05) and 0.93 (0.05) for low and high density, respectively]. This differential effect may, however, be a reflection of the fact that the hit rates were near ceiling.

Reaction times (RTs) for the two recognition tasks did not differ [Low density: Old, 1260 (182) ms; New, 1248 (120) ms. High density: Old, 1237 (93) ms; New, 1250 (148) ms]. RTs for the old items in the source task [1460 (237) ms] were slower than those for the corresponding items in the high density recognition task. This trend, which was evident in the RTs of five of the six subjects, approached significance [$t(5) = 2.32$, $P < 0.1$].

fMRI Data

Analysis of the fMRI data was focused on three preexperimentally motivated directional contrasts¹: (i) high vs low recognition, (ii) source vs high recognition, and (iii) source vs low recognition. Contrast (i) was conducted to identify regions activated to a greater extent in the high density condition than the low density condition of the recognition task. Contrast (ii) identified regions that were more active for source judgments than recognition judgments when the probability of successful item memory was high and equivalent across the two tasks. By comparing the outcomes of contrasts (iii) and (i), it was possible to ascertain whether the regions sensitive to target density during recognition were also sensitive to density when the task was source judgement.

The outcome of the first of these contrasts, between high and low density recognition, is shown in Table 1(a) and Fig. 1. Relative to the low density condition, high

¹ We describe here experimental effects in frontal cortex only, since the experiment was designed specifically to test hypotheses about retrieval-related activity in this region. Results for the entire brain can be obtained from the first author on request.

TABLE 1

Outcome of Contrasts for (a) High Density vs Low Density Recognition; (b) Source vs Low Density Recognition

| | Location | Peak Z (<i>n</i> voxels) | Region | BA |
|-----|-------------|------------------------------|--------------------------------|-------|
| (a) | -52, 12, 22 | 3.93 (43) | Left inferior frontal gyrus | 44 |
| | -44, 56, -2 | 3.67 (10) | Left anterior frontal | 10 |
| | 28, 46, 16 | 3.84 (33) | Right anterior frontal | 10/46 |
| | 42, 52, 10 | 4.00 (12) | Right anterior frontal | 10 |
| | 2, 2, 44 | 3.92 (17) | Right cingulate gyrus | 32/24 |
| (b) | -44, 0, 48 | 4.19 (45) | Left precentral gyrus | 6 |
| | -44, 4, 30 | 5.50 (85) | Left precentral gyrus | 6 |
| | -52, 12, 24 | 4.25 (51) | Left inferior frontal gyrus | 44 |
| | -36, 20, -8 | 4.93 (110) | Left frontal operculum | 47 |
| | -50, 26, -6 | 4.23 (87) | Left inferior frontal gyrus | 45/47 |
| | -54, 30, 14 | 4.24 (36) | Left inferior frontal gyrus | 45 |
| | -36, 50, 16 | 4.39 (26) | Left anterior frontal | 9 |
| | -28, 52, 0 | 4.11 (50) | Left frontal pole | 10 |
| | -42, 52, -4 | 3.83 (14) | Left frontal pole | 10 |
| | -4, 28, 34 | 4.31 (31) | Left medial frontal | 8 |
| | -4, 46, 28 | 4.12 (17) | Left medial frontal (anterior) | 9 |
| | 42, 16, -4 | 4.53 (77) | Right frontal operculum | 47 |
| | 58, 24, 22 | 4.05 (25) | Right inferior frontal gyrus | 44/45 |
| | 34, 48, 10 | 4.12 (75) | Right anterior frontal | 10 |
| | 46, 56, -6 | 3.67 (9) | Right frontal pole | 10 |
| | 6, 18, 48 | 4.34 (68) | Right medial frontal | 8 |

Note. Location is with respect to the system of Talairach and Tournoux (1988). *Z* values refer to the peak of the activated cluster, the size of which is indicated in brackets.

density recognition was associated with signal increases in two regions of left prefrontal cortex, as well as in right anterior prefrontal cortex in the vicinity of BA 10.

Table 2 and Fig. 2 show the results of the comparison between the source task and high density recognition. Signal increases were observed bilaterally in the frontal operculum and cingulate gyrus, in left inferior frontal gyrus, and in left anterior prefrontal cortex in the vicinity of BA 10. Apart from a small area of the

TABLE 2

Outcome of Contrasts for Source vs High Density Recognition

| | Location | Peak Z (<i>n</i> voxels) | Region | BA |
|--|-------------|------------------------------|--------------------------------|-------|
| | -44, 4, 30 | 4.36 (47) | left precentral gyrus | 6 |
| | -40, 18, 0 | 4.34 (66) | left inferior frontal gyrus | 45 |
| | -30, 22, 6 | 5.12 (33) | left frontal operculum | 45 |
| | -50, 28, 0 | 3.74 (24) | left inferior frontal gyrus | 45/47 |
| | -28, 46, 6 | 4.43 (47) | left anterior frontal | 10 |
| | -22, 60, 12 | 4.69 (28) | left frontal pole | 10 |
| | -6, 18, 38 | 3.83 (15) | left cingulate gyrus | 32 |
| | 42, 14, -4 | 3.83 (41) | right frontal operculum | 47 |
| | 42, 34, 18 | 3.64 (9) | right middle frontal gyrus | 46 |
| | 6, 16, 50 | 4.74 (32) | right posterior medial frontal | 6/8 |
| | 4, 22, 36 | 4.04 (15) | right cingulate gyrus | 32 |

Note. Location and *Z* values defined as for Table 1.

right middle frontal gyrus (BA 46), no differences in signal were apparent in right anterior or dorsolateral prefrontal regions. The outcome of the contrast between the source task and low density recognition can be seen in Table 1(b) and Fig. 3. For medial and left prefrontal cortex the results were largely similar to those seen for the preceding contrast. In the right hemisphere, however, two additional regions—posterior inferior frontal gyrus and anterior cortex (BA 10)—were more active in the source task.

In summary, the foregoing results indicate that relative to low density recognition, high density recognition and source memory engaged right anterior prefrontal cortex (BA 10) to a similar extent, but gave rise to differential activation in several other prefrontal regions, including left BA 10. The different patterns of activity in left and right anterior prefrontal cortex (BA 10) are illustrated in Fig. 4, where mean signal intensity is plotted for representative voxels in each of these regions.

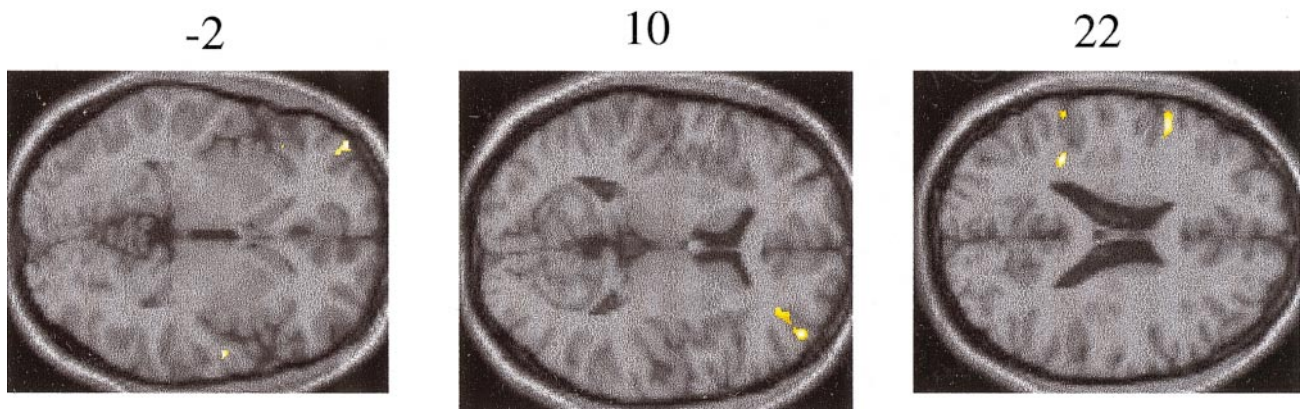


FIG. 1. Statistical parametric maps (threshold $P < 0.005$) of the outcome of the contrast between the high and low density conditions of the recognition task, superimposed onto transverse sections ($z = -2, 10, \text{ and } 22$) of a magnetic resonance brain image, which has been transformed into standard space (Talairach and Tournoux, 1988).

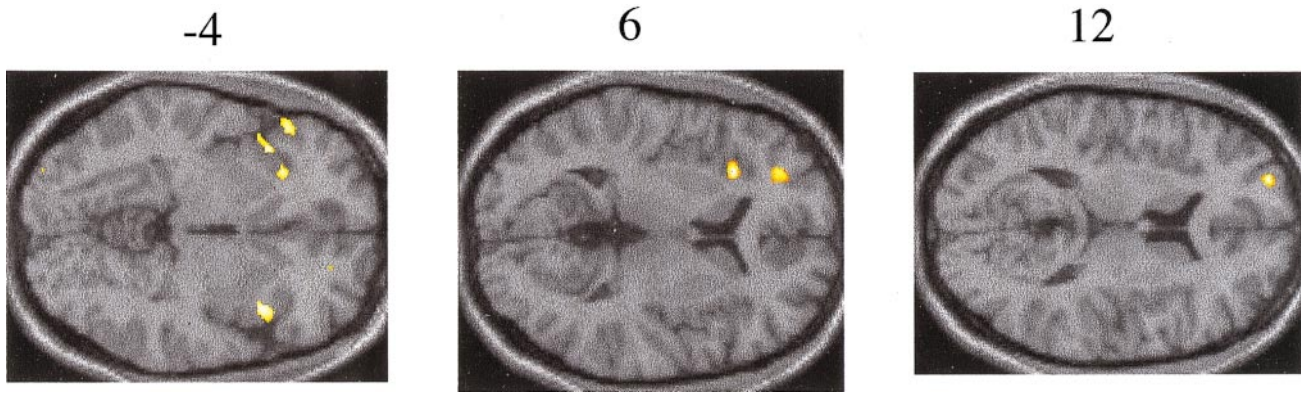


FIG. 2. Statistical parametric maps (threshold $P < 0.005$) of the outcome of the contrast between the source task and the high density condition of the recognition task, superimposed onto transverse sections ($z = -4, 6,$ and 12) of the same magnetic resonance brain image shown in Fig. 1.

DISCUSSION

The primary aim of this study was to address two questions. First, does a requirement to make source judgments further increment activity in right prefrontal regions that are activated by old items in a recogni-

tion memory test? Second, does a source memory task engage left prefrontal cortex to a greater extent than simple recognition? According to the present findings, the answer to the first question is negative. Of the regions in which activity was greater for high than for low density recognition, none showed additional activation

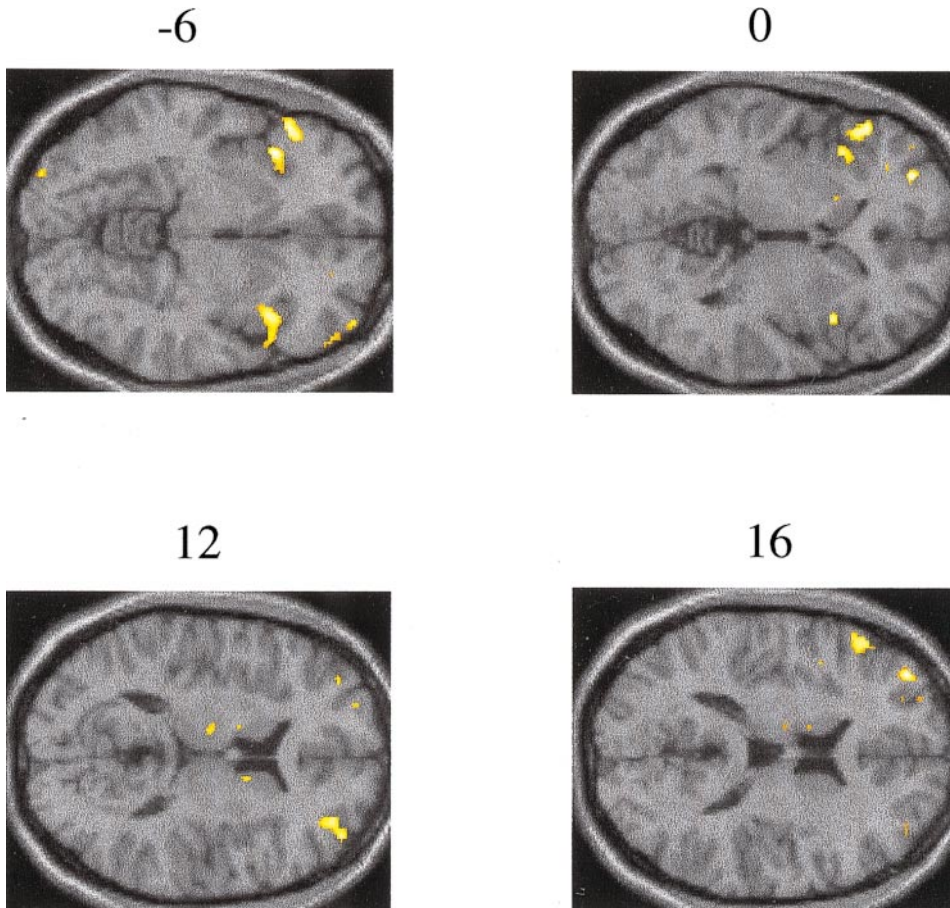


FIG. 3. Statistical parametric maps (threshold $P < 0.005$) of the outcome of the contrast between the source task and the low density condition of the recognition task, superimposed onto transverse sections ($z = -6, 0, 12,$ and 16) of the same magnetic resonance brain image shown in Fig. 1.

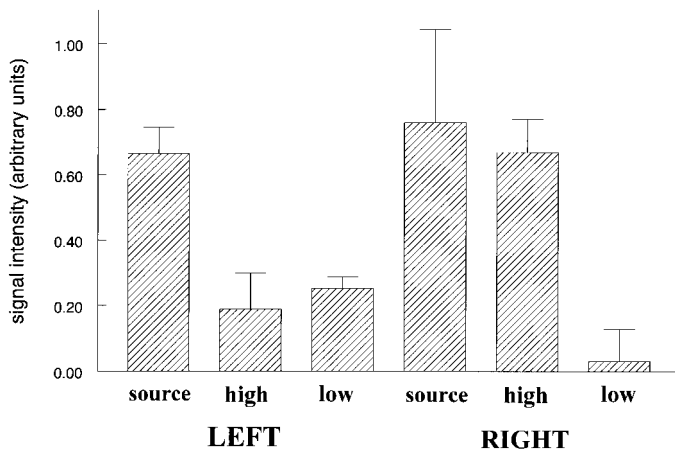


FIG. 4. Mean signal intensity (arbitrary units) in left ($x = -28$, $y = 46$, $z = 6$) and right ($x = 42$, $y = 52$, $z = 10$) anterior prefrontal cortex during source memory, high density recognition, and low density recognition. Bars represent the standard errors of each subject's mean across-block intensity values for the voxels and conditions indicated.

during the source memory task. By contrast, the answer to the second question is affirmative; relative to recognition, the source task engaged several additional prefrontal regions. Some of these task-related effects were bilateral, whereas others were confined to the left hemisphere.

Below, we focus first on the implications of these findings for current ideas about the roles of left and right anterior prefrontal cortex in memory retrieval. We then discuss the possible significance of the findings for an understanding of the roles played during episodic retrieval by other prefrontal regions. Finally, we attempt to reconcile the findings from neuroimaging and electrophysiological studies of source memory.

Anterior Prefrontal Cortex

The finding of greater activity in regions of right anterior prefrontal cortex for high density than for low density recognition replicates the results of two PET studies (Rugg *et al.*, 1996, 1998; see also Buckner *et al.*, 1998) and is consistent with the hypothesis that this region is sensitive to the probability of successful retrieval (but see Wagner *et al.* (1998) for an alternative interpretation of such findings). The contrast between the source and low density recognition conditions revealed that these right anterior regions were also engaged in the source task, consistent with much previous evidence that the involvement of right prefrontal cortex in episodic retrieval is not associated with any one particular retrieval task (for review see Fletcher *et al.*, 1997). The finding that the activity of these right anterior prefrontal regions was not enhanced during source memory is, however, inconsistent with the hypothesis (see Introduction) that right anterior prefrontal activity is sensitive to the load placed on postretrieval processing, since the load is assumed to be greater for

judgments of source than for judgments of recognition (an assumption supported perhaps by the tendency for RTs to be longer in the former task). Evidently, whatever the identity of the cognitive operations supported by the right anterior prefrontal cortex, they were engaged to a similar extent during the high density recognition and source memory tasks. The proposal of Nolde *et al.* (1998a) that the right prefrontal cortex supports "heuristic" processes, sufficient to permit a rudimentary evaluation of retrieved information, but not its more detailed analysis, is consistent with these findings.

It is important to note, however, that our finding that the right anterior prefrontal cortex is equally active during recognition memory and source judgment is subject to two caveats. First, and most obvious, the conclusion is predicated on a null result, that is, the failure to find a difference between the tasks. As always in such cases, the possibility that a difference would have emerged in a study with greater power cannot be ruled out.

Second, it is conceivable that differences between the tasks were diluted because subjects attempted to retrieve and make use of source information regardless of the task instructions.² Clearly, the more similar the information and strategies employed in the two tasks, the more similar their respective neural correlates. However, this account cannot easily explain why prefrontal regions other than right anterior cortex did show greater activity in the source task (see below).

In contrast to the findings for right anterior prefrontal cortex, two regions ($x, y, z = -28, 46, 6$, and $-22, 60, 12$, respectively) of left anterior prefrontal cortex were more active in the source task than in either recognition condition. This finding adds to evidence linking left prefrontal cortex to the retrieval of source information (Nolde *et al.*, 1998b, Henson *et al.*, 1999). The interpretation of these results is complicated by the fact that it is not possible to determine whether they reflect (i) a "state" effect associated with mere engagement in the source task, (ii) stimulus-related processing common to both old and new items, or (iii) operations carried out specifically on the products of memory retrieval, and hence selective for old words.³ Whatever the explanation, the results presumably reflect the additional

² We thank an anonymous referee for drawing this point to our attention.

³ In principle, further light could have been shed on this issue in the present study by the employment of a "low density" as well as a "high density" source task. In practice, however, the value of this condition would have been limited by the difficulty of convincing subjects of the meaningfulness of source judgments on lists consisting largely of items they failed to recognize as studied. The issue is much better addressed by the employment of event-related designs (Josephs *et al.*, 1997; Rosen *et al.*, 1998), permitting responses to old and new words to be characterized separately. Such a design was employed by Nolde *et al.* (1998b). In that report, however, data are reported only for items collapsed across the old/new dimension. It is therefore not possible to determine whether any of the effects described in the report are modulated by the test items' study status.

processing demands engendered by the requirement to perform source rather than simple recognition judgments.

According to Nolde *et al.* (1998a) these demands are captured by such terms as “reflective,” “systematic,” or “complex” processing, terms which refer to a wide range of cognitive processes hypothesized to be engaged during episodic retrieval (Johnson, 1993) and to be supported by left prefrontal cortex. Testing this proposal will require the development of procedures that allow these different putative processes to be operationalized and thus brought under experimental control. An alternative possibility is that the additional prefrontal activity (both in anterior cortex and elsewhere) observed during source judgments relative to recognition merely reflects the extra effort required to perform such judgments, which are invariably more difficult than simple recognition of the same items (see Buckner *et al.*, 1996, for data supporting a role for left prefrontal and bilateral opercular regions in effortful retrieval). This possibility can be tested by an orthogonal manipulation of type of task and task difficulty. Finally, it should be noted that both the present study and that of Henson *et al.* (1999) employed words as experimental items, while Nolde *et al.* (1998b) employed a mixture of words and pictures at study, and words alone at test. It therefore remains to be demonstrated that the recruitment of additional left anterior prefrontal regions in source memory is not a material specific effect tied to the use of words as test cues, reflecting, perhaps, the reinstatement or attempted reinstatement of study processing diagnostic of source (Henson *et al.*, 1999).

In contrast to the left anterior prefrontal regions discussed above, a quite different pattern of results was observed in a nearby, more lateral region ($x,y,z = -44,56,-2$). Here, as was found in Rugg *et al.* (1996), left anterior prefrontal activity was greater during high density than low density recognition. Essentially the same region was also more active in the source task than it was in low density recognition, but to no greater extent than in the case of high density recognition. Thus, unlike the more medial left anterior prefrontal regions discussed above, the pattern of activity shown by this lateral region mirrored the pattern found in right anterior prefrontal cortex. If this finding is to be reconciled with the view that left lateralized prefrontal activations during episodic retrieval invariably reflect “complex” or “reflective” processing (Nolde *et al.*, 1998a), it must be assumed that some aspects of such processing were engaged equivalently by the high density recognition and source memory tasks, whereas other aspects were engaged to a greater extent during the source task. The present findings are equally compatible, however, with the proposal that the retrieval-related operations supported by the right anterior prefrontal cortex are not exclusively right lateralized, but are supported by left anterior prefrontal

cortex also, albeit to a lesser degree. Regardless of the relative merits of these alternatives, the finding of different patterns of task-related activity in almost adjacent portions of left anterior prefrontal cortex indicates that there is considerable functional heterogeneity in this region. Its role in episodic memory retrieval is therefore unlikely to be specifiable in terms of a single cognitive operation.

Dorsolateral Prefrontal Cortex

In contrast to the right anterior prefrontal cortex (BA 10), a restricted region of right dorsolateral cortex in the vicinity of BA 46 showed greater activity during the source than the high density recognition task (see Table 2). This finding echoes the results of Henson *et al.* (1999), who reported that, relative to simple recognition, source judgments were associated with enhanced activity in a restricted region of BA 46, at a site ($x,y,z = 48,30,21$) close to the peak reported here ($x,y,z = 42,34,18$). Henson *et al.* (1999) interpreted this additional dorsolateral activity during their source task as reflecting the greater demands made by this task on “monitoring” operations (Fletcher *et al.*, 1998). This interpretation is akin to the postretrieval processing hypothesis advanced to account both for previous PET studies of target density (Rugg *et al.*, 1996, 1998) and for ERP findings (Rugg and Allan, in press). A similar account is possible in the present study, but would not easily explain the failure to find differences in right dorsolateral activity in the contrasts between source and low density recognition, or, for that matter, between the two recognition conditions. While this might be achieved by making an *ad hoc* assumption about the relative “monitoring” demands of the three retrieval conditions, it must be conceded that this pattern does not admit a straightforward explanation.

Inferior Prefrontal Cortex and Frontal Operculum

Relative to either version of the recognition task, increased activity in the frontal operculum (BA 47) was observed bilaterally during the source task. Opercular activation has been described previously in studies of memory retrieval, both bilaterally (e.g., Buckner *et al.*, 1998; Wagner *et al.*, 1998) and confined to the right hemisphere (e.g., Fletcher *et al.*, 1998; Henson *et al.*, 1999). Fletcher *et al.* reported that right opercular/ventral prefrontal activation was greater in a condition in which external retrieval cues were continuously varied, relative to a condition in which retrieval was self-directed in the absence of external cues. They argued, as did Henson *et al.* (1999), that this region supported the processes involved in “cue specification,” the conversion of retrieval cues into “descriptors” that could be used to direct memory search (Burgess and Shallice, 1996). From this perspective, the present findings would reflect the greater load placed on cue

specification processes by the source task than by recognition. Since the informational requirements of the two tasks differ (the source task requiring the retrieval of more detailed information about the study episode than recognition), it is not implausible that test items might be used to generate more elaborate descriptors in one task than the other.

As noted by Wagner *et al.* (1998), however, activation of the frontal operculum in the vicinity of BA 47, albeit mainly on the left, has been reported in semantic and phonological processing tasks with no overt episodic retrieval component (see Fiez, 1997, for review). While it is conceivable that right and left opercular regions might support operations as distinct as “cue specification” and the semantic/phonological processing of words, it seems equally likely that opercular activation during memory tasks reflects cognitive operations, such as the internal “rehearsal” of test items, that are not tied specifically to memory retrieval. The same conclusion seems likely to hold for the retrieval-related inferior prefrontal gyrus (BA 45) activations observed in the present study. These regions have also been found to be active in a variety of language-related tasks, especially those including a working memory component (e.g., Awh *et al.*, 1996), and their activation in the present study may reflect differences in the demands placed upon articulatory/phonological processing across the three different retrieval conditions.

Relationship between Functional Imaging and ERP Findings

The hypothesis motivating the present experiment—that right prefrontal regions activated during high density recognition would show further enhancement of activity when the task was source memory—was based on the results of ERP studies (e.g., Rugg *et al.*, 1998b; Wilding and Rugg, 1996, 1997). A consistent finding in these studies was that, relative to new test items, ERPs elicited by old items attracting correct source judgments exhibited a sustained, positive-going wave that was maximal over the right frontal scalp. On the assumption that the “right frontal” ERP effect originates in the right prefrontal cortex, the question arises how these findings can be reconciled with the present and previous (Nolde *et al.*, 1998b; Henson *et al.*, 1999) neuroimaging results, which indicate that source judgements are associated with bilateral prefrontal activation which is stronger on the left than the right. For two reasons, these seemingly disparate sets of findings may not in fact be at variance with one another. First, as already noted, it cannot be determined from the available evidence whether the left-sided activations associated with source memory are greater for old than for new items, as appears to be the case for activation of right prefrontal cortex. If old and new items activate left prefrontal cortex to an equal

extent, then activity in this region would not contribute to ERP “old/new” effects.

Second, the neuroimaging data give no information about the relative time-courses of the activation of right and left prefrontal cortices during source judgments. Even if left and right prefrontal regions are both activated selectively by old items, it does not follow that these activations have equivalent time-courses. Thus, the right frontal ERP effect could be a reflection of right prefrontal activity which outlasts the activity elicited on the left. The observation that the right frontal ERP effect is sometimes preceded by an earlier-onsetting bilateral (Donaldson and Rugg, 1998; Wilding and Rugg, 1997), or left lateralized (Schloerscheidt and Rugg, 1998), old/new effect is consistent with this possibility.

Concluding Comments

In summary, the results of the present study offer only limited support for the hypothesis that activation of the anterior right prefrontal cortex during episodic memory retrieval reflects the engagement of processes that operate on the products of retrieval in the furtherance of behavioral goals (the postretrieval processing hypothesis). Consistent with the hypothesis, the manipulation of target density in a recognition memory task modulated right anterior prefrontal activity. But adding to the load on postretrieval processing by requiring source rather than recognition judgments had no further effect on activity in this region, and instead resulted in activation of anterior prefrontal cortex on the left. Along with other, similar, findings (Nolde *et al.*, 1998b; Henson *et al.*, 1999), these results suggest that the left anterior prefrontal cortex plays an important role in the retrieval of source information.

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