ELSEVIER

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 21 (2004) 1337–1349

Functional-anatomic correlates of remembering and knowing

Mark E. Wheeler[a,*] and Randy L. Buckner[a,b,c]

[a] *Departments of Psychology and Radiology, Washington University in St. Louis, St. Louis, MO 63130,USA*
[b] *Department of Anatomy and Neurobiology, Washington University in St. Louis, St. Louis, MO 63110, USA*
[c] *Howard Hughes Medical Institute, St. Louis, MO 63110, USA*

Received 19 June 2003; revised 5 November 2003; accepted 13 November 2003

Neural correlates of remembering were examined using event-related functional MRI (fMRI) in 20 young adults. A recognition paradigm based on the remember/know (RK) procedure was used to separately classify studied items that were correctly identified and accompanied by a conscious recollection of details about the study episode from studied items that were correctly identified in the absence of conscious recollection. To facilitate exploration of the basis of remember decisions, studied items were paired with pictures and sounds to encourage retrieval of specific content during scanned testing. Analyses using a priori regions of interest indicated that remembering recruited both regions that associate with the perception and/or decision that information is old and regions that associate preferentially with visual content, while knowing recruited regions associated with oldness, but did not recruit visual content regions. Exploratory analyses further indicated a functional dissociation across regions of parietal cortex that may aid to reconcile several divergent results in the literature. Lateral parietal regions responded preferentially to remember decisions, while a slightly medial region responded robustly to both remember and know decisions. Taken collectively, these results suggest that remembering and knowing associate with common processes supporting a perception and/or the decision that information is old. Remembering additionally recruits regions specific to retrieved content, which may participate to convey the vividness typical of recollective experience.

Keywords: Episodic; Memory; Remember; Know; Neuroimaging; fMRI

Remembering is the act of becoming aware again of an episode that has occurred in one's own past (Bartlett, 1932; James, 1890; Tulving, 1983, 1985). When we remember, details uniquely associated with an earlier episode are brought to awareness that distinguish it from the myriad of other possible episodes accessible in memory. The details, or contents of a memory, can include thoughts, emotions felt at an event, and sensory experiences such as the appearance of a face or scene. Additionally, remembering is accompanied by an awareness that the experience is from the rememberer's past and is not imagined or experienced in the present. The present experiment focuses on neural correlates of two distinct components of remembering—the retrieval of specific content and the perception that processed information is from the past. We explore these components with a recognition paradigm based on the remember/know (RK) procedure (Gardiner and Richardson-Klavehn, 2000; Tulving, 1985).

Previous experiments have associated episodic remembering with brain regions generally involved with controlled processing, and also with specific medial temporal and neocortical structures that may make selective contributions to different components of remembering (for reviews, see Buckner and Wheeler, 2001; Cabeza and Nyberg, 2000; Desgranges et al., 1998; Rugg et al., 2002; Schacter and Wagner, 1999). In terms of retrieved content, growing evidence suggests that certain regions of the brain that process incoming sensory information can also be involved in the subsequent retrieval of that information from memory (Desimone et al., 1995; Farah, 1989; Ishai et al., 2000; Köhler et al., 1998; Kosslyn et al., 1993, 1995; Mellet et al., 2000; Miyashita, 1988; Nyberg et al., 2000, 2001; O'Craven and Kanwisher, 2000; Owen et al., 1996; Roland and Gulyás, 1995; Rösler et al., 1995; Wheeler and Buckner, 2003; Wheeler et al., 2000; Zatorre et al., 1996). For example, Wheeler et al. (2000; see also Wheeler and Buckner, 2003) found that retrieval of picture and sound information reactivated subsets of regions that were active during perception of the same information. Similarly, Nyberg et al. (2000) found increased activity in auditory cortex during retrieval of words that had been previously studied with sounds, even when subjects were not explicitly instructed to retrieve sound information. Regions within visual cortex that are reactivated during mental imagery have also been demonstrated to vary according to the type of visual information retrieved. For instance, imagining different categories of visual objects (e.g., faces and houses) is associated with differential activity in regions of visual cortex that respond preferentially to those object classes (Ishai et al., 2000; O'Craven and Kanwisher, 2000). These experiments indicate that when we remember episodes from our past, reactivation can include regions preferentially associated with the type of information being retrieved.

Memory experiments using event-related potential (ERP), positron emission tomography (PET), and functional MRI (fMRI) methods have also identified frontal and parietal regions that are active when recently studied items are correctly identified (i.e., hits) relative to when new items are correctly rejected (often called the old/new, or retrieval success, effect) (Donaldson et al., 2001b;

---

* Corresponding author. Department of Radiology, Washington University in St. Louis, Campus Box 8111, 4525 Scott Avenue, St. Louis, MO 63108.

E-mail address: mw@npg.wustl.edu (M.E. Wheeler).

1053-8119/$ - see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2003.11.001

Düzel et al., 1997; Habib and Lepage, 1999; Henson et al., 1999; Konishi et al., 2000; McDermott et al., 2000; Velanova et al., 2003; Wilding and Rugg, 1996; Wilding et al., 1995). Suggesting a contribution to remembering that is distinct from the content-specific reactivation patterns discussed above, regions activated to hits over correct rejections have generalized across a wide range of task paradigms that include retrieval of multiple forms of information. Among these regions, left parietal cortex [approximate Brodmann's area (BA) 40/39] has been consistently associated with successful retrieval of information from the past (Donaldson et al., 2001b; Habib and Lepage, 1999; Henson et al., 1999; Konishi et al., 2000; McDermott et al., 2000). In a recent fMRI memory experiment (Wheeler and Buckner, 2003), BA 40/39 not only increased activity when previously studied items were correctly identified (hits), but also increased activity when new, unstudied, items were mistakenly judged to be old (false alarms) indicating that activity was sensitive to the subjects' perception or decision that the items had been experienced in the context of the experiment. Donaldson et al. (2001a) noted that left parietal activation to hits occurred for trials in which retrieval decisions were made rapidly, suggesting a process that could be achieved, under the right conditions, with minimal controlled processing. McDermott et al. (2000) found a left parietal region that was more active for hits than for correctly rejected new compound words. Interestingly, when the lexical units of the studied compound words (e.g., 'nose' and 'dive' for 'nosedive') were rearranged to form new, nontarget, words (e.g., 'skydive'), activity in left parietal cortex was greater for correctly identified but rearranged compound words than for new compound words. Both rearranged and new compound words were nontargets, with the only difference being that the rearranged nontargets had been experienced previously in the context of the experiment, a difference of which the subjects were likely aware.

Combined, results from these experiments suggest that activity in certain regions of left parietal cortex is related to our perception or decision that retrieved information is from the past. However, there is also evidence that activity in left parietal cortex is more related to recollective than nonrecollective processes (i.e., familiarity) (e.g., Cansino et al., 2002; Dobbins et al., 2002; Donaldson and Rugg, 1998; Henson et al., 1999; Smith, 1993; Wilding and Rugg, 1996). For example, using ERP, Donaldson and Rugg (1998) had subjects study pairs of words and then gave them a memory test in which they were given both intact, rearranged, and new pairs. Under the assumption that intact pairs were recognized based more on recollection and rearranged pairs more on familiarity, scalp potentials showed differential effects over left parietal (and right frontal) cortex when decisions were based on recollection than when based on familiarity. Similarly, using a remember/know procedure combined with fMRI, Henson et al. (1999) identified a region in left parietal cortex that was more active during remembering than knowing. However, Henson et al. (1999) also found a more anterior and medial parietal region that responded similarly for remembering and knowing (both greater than new items) (in Henson et al., compare Fig. 1 with Fig. 3). Therefore, the processing specificity and functional topography of left parietal cortex remains unclear, at least insofar as memory retrieval is concerned.

Understanding the contributions of these cortical regions to memory may provide insight into distinct forms of retrieval, including the prominent distinction between recollection- and familiarity-based retrieval (Jacoby, 1991; Mandler, 1980; for a recent review, see Yonelinas, 2002). If sensory processing regions support retrieval of sensory-related content during remembering, and if specific regions within left parietal cortex (among other regions) associate with the perception or decision that information is from the past, recollection-based memory retrieval might arise when activity in both sensory processing (or other content-based regions) and parietal regions are simultaneously present. When memory is based on nonrecollective processes (e.g., familiarity), information might still be perceived as having been experienced in the past via activation of left parietal and other regions associated with the generic perception that information is old. By this view, certain component processes are shared between recollection and familiarity with the *absence* of retrieval-related activity in content regions being a fundamental difference between those retrieval events experienced as full-blown recollection and those experienced as having a more impoverished, limited quality of familiarity (Buckner and Wheeler, 2001).

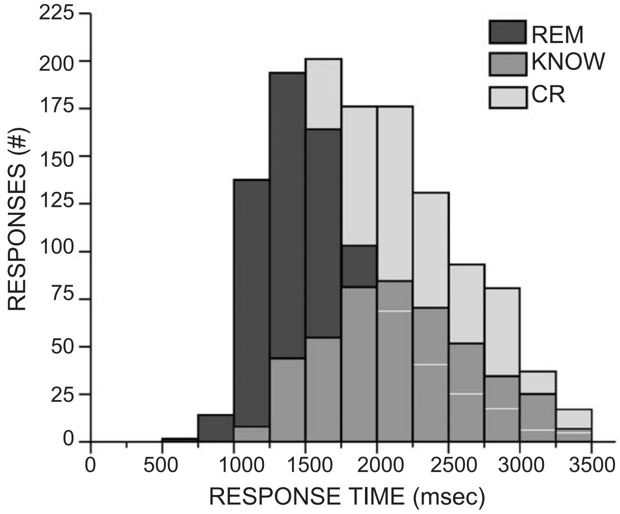

Fig. 1. Response time (RT) distributions are plotted for REMEMBER (middle layer), KNOW (front layer), and CR (back layer) conditions. Each bar displays the number of responses for each 250 ms bin throughout the 3540-ms trial. The white horizontal lines in the KNOW distribution indicate the number of REMEMBER responses.

To test these possibilities, we explored, using event-related fMRI, a remember/know recognition paradigm in which word cues were studied with picture and sound associates. The remember/know paradigm was developed as a method to examine different states of conscious awareness supporting memory retrieval (Tulving, 1985) and has since been studied extensively (e.g., Gardiner and Java, 1993; Gardiner and Richardson-Klavehn, 2000; Rajaram, 1993). Within the imaging literature, variants of this task have recently been studied using event-related fMRI (Eldridge et al., 2000; Henson et al., 1999). The goal of the remember/know procedure is to determine whether previously studied items are recognized because they are accompanied by a conscious recollection, or reexperiencing, of the original episode (remembering), or because the items are recognized based more on a feeling of familiarity, in the absence of recollection about the study session (knowing). Importantly, in this experiment, some test items (words) were paired with pictures or sounds during the study phase to give participants the opportunity to recollect visual or auditory content during the scanned remember/know test. New, unstudied, words were included at test to examine modulations based on study history. We predicted that remembered items, relative to new items, would be associated with increased activity in both parietal cortex and in visual processing regions that have been previously associated with object processing and retrieval. Also, relative to new items, known items would be associated with increased activity in parietal cortex, but with similar levels of activity in object processing regions. Additional exploratory analyses are presented that indicate an unanticipated functional dissociation across regions of parietal cortex that may aid to reconcile several divergent results in the literature.

Methods

Subjects

Twenty five right-handed subjects from the Washington University community participated. Of these, one was excluded from analysis due to excessive movement during imaging (>1 mm within-run movement), two for failure to comply with task instructions, and three for having an insufficient number of know responses for functional imaging analyses (<9). The remaining 20 subjects (seven females) ranged in age from 18 to 32 years (mean 23 years), had normal or corrected-to-normal vision, were native English speakers, and reported no history of significant neurological problems. Subjects provided informed consent in accordance with the Washington University Human Studies Committee and were paid for their participation.

Study phase

Subjects studied a set of 300 words one time. Words were presented for 750 ms at the start of each 5-s trial. Half of the words were immediately followed by pictures (mix of color–grayscale; 3-s duration), the other half by sounds (1–2.5 s duration) (see Wheeler and Buckner, 2003; Wheeler et al., 2000). Subjects were instructed to memorize the words for a later test and to press one of two buttons depending on whether they saw a picture or heard a sound after each word. Subjects were not explicitly instructed to memorize the pictures and sounds. Words were paired with pictures at study to provide specific visual object content that could be used to facilitate subsequent retrieval. Sounds were included to reduce the possibility that, at test, subjects would enter a general mode or state in which they were always prepared to retrieve visual information (e.g., Kanwisher and Wojciulik, 2000; Kastner et al., 1999; Shulman et al., 1997b, 1999).

Study words were drawn from a pool of 450 total words that were divided into three stimulus lists. Two of the lists (PictureA, PictureB) consisted of 150 words, each paired with a unique picture related to the word (i.e., DOG paired with a picture of a dog). A third list (Sound) consisted of 150 different words, each paired with a unique sound related to the word. Half of the subjects studied lists PictureA and Sound, while the other half studied lists PictureB and Sound. Trial types were presented in pseudo-random order, with no more than two of any trial type in succession. The three lists were equated for (1) word length (range: 3–13 letters; mean = 6.3), (2) word frequency based on norms reported by Francis and Kucera (1982) (range: 1–352 instances per million; mean = 18), and (3) for the PictureA and PictureB lists, picture width (range: 0.8–8.0° visual angle; mean = 3.9°). Word stimuli were presented in black 24-point Geneva bold font centered on a white background using a Power Macintosh G4 with PsyScope software (Cohen et al., 1993). Responses were made using a PsyScope Button Box (Carnegie Mellon University, Pittsburgh, PA) and recorded by PsyScope.

Scanned recognition task

After a 24- to 36-h delay, subjects were given a scanned recognition memory test in which studied (old) words were intermixed with new words. Test instructions and training procedures were adapted from Rajaram (1993) and were similar to those used by Moscovitch and McAndrews (2002). For each word, subjects decided whether it was (1) remembered from the study list, (2) known to be on the list but not remembered, (3) new, or (4) guessed. Subjects were instructed to make a remember response if the word brought back to mind a conscious recollection of its prior occurrence in the study list, to make a know response for recognized words that were not accompanied by conscious recollection, and to make a new response for words that were not recognized (note that 'remember', 'know,' or 'new' terms in lower case refer to test responses, while terms in upper case refer to conditions used in data analyses). Subjects were also instructed to respond remember, know, or new only if they were confident in their decision and to respond with a fourth button, guess, if they thought they were guessing. The guess response option decreases the tendency for subjects to use remember and know responses for higher and lower confidence responses, respectively (i.e., Gardiner et al., 1998, 2002). Testing began only when subjects could describe examples of remembering and knowing to the experimenter. Subjects used the middle and index finger of both hands to respond, with response-to-hand mappings mapping counterbalanced across subjects. Remember and know responses were always made using the same hand (whether left or right), and new and guess responses were made using the other hand. Subjects were trained on the response mapping before testing.

The test was divided into five fMRI runs. Each run consisted of 20 words that were studied with pictures (*pic*), 5 words studied with sounds (*snd*), 20 new words (*new*), and 20 fixation cross-hairs (*fix*), for a total of 100 *pic*, 25 *snd*, 100 *new*, and 100 *fix* trials per subject. *Pic* test cues were selected by dividing the study list (PictureA or PictureB) into three subgroups of 50 words each and selecting two of the subgroups, according to counterbalancing criteria, for a total of 100 cues. *New* cues were selected using the same procedure but were drawn instead from the unstudied list. Subgroup assignment was counterbalanced across subjects. *Snd* cues were chosen randomly (without replacement) from the Sound list, with the list re-sorted when exhausted. During each nonfixation trial, a word cue appeared on the screen for 750 ms followed by 2790 ms of fixation, for a total of 3540 ms. Pictures and sounds were not presented during the test. Trial types were pseudo-randomly ordered such that each trial type was preceded and followed by each other trial type equally often (Buckner et al., 1998a).

Imaging procedures

Functional imaging was conducted on a Siemens 1.5-T Vision System (Erlangen, Germany). Visual stimuli were generated on an Apple Power Macintosh G4 using PsyScope (Cohen et al., 1993) and projected, using a Sharp LCD PG-C20XU projector, onto a screen positioned at the head of the magnet bore. Subjects viewed the screen using a mirror attached to the head coil (approximate distance from mirror to screen 164 cm). Words were presented in black 24-point Geneva bold font, centered on a white background. Headphones were used to dampen scanner noise. Subjects responded by pressing one of four different buttons on a fiberoptic light-sensitive key-press interfaced with a PsyScope Button Box (Carnegie Mellon University). Due to equipment limitations, response times were not recorded for one button. This button was always assigned to the guess response and subjects were unaware of this fact. Foam pillows and a thermoplastic facemask were used to minimize head movement. In each session, structural images were acquired first using a sagittal MP-RAGE T1-weighted sequence [repetition time (TR) = 9.7 ms, echo time (TE) = 4 ms, flip angle = 10°, inversion time (TI) = 20 ms, delay time (TD) = 500 ms]. Five functional runs, each including 111 acquisitions of 16 contiguous 8-mm-thick axial images, were then collected using an asymmetric spin-echo echo-planar imaging sequence sensitive to blood-oxygen-level-dependent (BOLD) contrast (T2*) (TR = 2.36 s, TE = 37 ms, 3.75 × 3.75 mm in-plane resolution) (Kwong et al., 1992; Ogawa et al., 1992). This sequence allows complete brain coverage at a high signal-to-noise ratio (Conturo et al., 1996). Images were aligned to the plane of the anterior commissure and posterior commissure (AC-PC). The first four images in each run were discarded to allow magnetization to stabilize. Because trial durations were 3540 ms, which was 1.5 times the TR, half of the trials began at the beginning of the image acquisition and half began in the middle of the acquisition. This procedure allows a better temporal sampling of the hemodynamic response (Josephs et al., 1997; Miezin et al., 2000).

Functional MRI data analysis

Functional MRI data were first preprocessed to correct for odd/even slice intensity differences and motion using a rigid-body rotation and translation correction (Snyder, 1996). Between-slice timing differences caused by slice acquisition order were adjusted using sinc interpolation, and the linear slope was removed on a voxel-by-voxel basis to correct for drift (Bandettini et al., 1993).

Functional MRI data were then selectively averaged (Buckner et al., 1998a; Dale and Buckner, 1997) into the following categories for analyses: (1) REMEMBER: items that were studied with pictures and correctly identified with a remember response, (2) KNOW: items studied with pictures and correctly identified with a know response, (3) MISS: items studied with pictures and incorrectly identified with a new response, (4) CR: items correctly identified as new (correct rejections), and (5) FIX: baseline fixation cross-hairs (+). Functional data for new items that were incorrectly identified (false alarms, FA) with remember (FA-REM) or know (FA-KNOW) responses were not analyzed because only seven (of 20) subjects had at least 10 responses (though behavioral data can be found in the Results). Items paired with sounds at study, guesses, and items for which no response was provided were also not included in functional analyses. Note that because the guess responses could not be recorded, the proportion of guess responses listed in Table 1 may slightly overestimate the actual number of guesses because non-responses were unavoidably included. Behavioral experiments estimate the non-response rate at 1–2%, suggesting that this bias is minimal. Individual subject fMRI data were normalized to a mean magnitude value of 1000 and transformed into a common atlas space based on the Talairach and Tournoux (1988) atlas (using 2-mm isotropic voxels).

Events of interest were initially time-locked to the behavioral response, rather than stimulus onset, to account for the marked variability in RT distributions among conditions (see Fig. 1) (Maccotta et al., 2001). Subsequent analyses were carried out in which events of interest were time-locked to stimulus onset. Because there were few notable differences among these approaches in the current data set, results from the original, response-locked, analyses are presented by default. However, results from both analyses are included for two critical hypothesis-driven regions, left BA 20 and left BA 40/39 (see Hypothesis-driven regional analyses). Fixation trials were always time-locked to stimulus onset. Events were sorted into bins of 2.36 s (equivalent to the TR) to generate time courses and statistical activation maps.

Hypothesis-driven regional analyses

Hypothesis-driven analyses were carried out on a set of inferior temporal and parietal regions obtained from previous memory experiments (described below) to examine responses during remembering and knowing. Hypothesis-driven analyses are particularly effective because they use regions of interest derived from independent data sets, and provide more power due to a decreased number of multiple comparisons and also because of averaging across many voxels within each region.

A left anterior occipital sulcus (AOS) region near *BA 19/37*, with peak atlas (Talairach and Tournoux, 1988) coordinates at $x = -36$, $y = -73$, $z = -12$, and a left anterior fusiform region near *BA 20* (−25, −37, −20), were both initially obtained from an experiment by Maccotta and Buckner (2002) that compared activity associated with visual processing of unscrambled vs. scrambled objects. BA 19/37 and BA 20 were two of the visual processing regions found to be more active for intact than for scrambled objects. In a subsequent experiment (Wheeler and Buckner, 2003; see also Wheeler et al., 2000), these regions were found to also reactivate selectively during retrieval of visual object

Table 1
Proportion of remember, know, and new responses to old and new words, and response times

Response	Old items				New items			
	Rem	Know	New	Guess	Rem	Know	New	Guess
Proportion								
Mean	0.39	0.23	0.29	0.08	0.11	0.18	0.59	0.11
SE	0.03	0.02	0.03	0.02	0.02	0.02	0.04	0.03
RT (ms)								
Mean	1663	2168	2132	NA	1953	2205	2001	NA
SE	50	71	75	NA	75	73	63	NA

Notes. Rem = remember; SE = standard error of the mean; RT = response time; NA = not available.

information from long-term memory, with the strongest modulation found in BA 20. In the current experiment, these regions were predicted to support visual object content for remember responses that were based on concurrent retrieval of picture information.

Left parietal cortex near the intraparietal sulcus (~BA 40/39) appears to be associated with the perception or decision that information is old. Left BA 40/39 has been found to increase activity when studied items are correctly recognized (e.g., Habib and Lepage, 1999; Konishi et al., 2000) and when new items are mistakenly endorsed as old (Wheeler and Buckner, 2003). Correctly rejected new items are typically associated with minimal activity in this region of left parietal cortex. A parietal region encompassing the left intraparietal sulcus (−39, −55, 36) was selected from a recognition experiment using word stimuli by Konishi et al. (2000). If this BA 40/39 region is associated with a perception of and/or decision about oldness during retrieval, then it should be more active for the REMEMBER and KNOW conditions than for the NEW condition. However, some ERP (Donaldson and Rugg, 1998; Rugg et al., 1996; Smith, 1993; Wilding and Rugg, 1996; Wilding et al., 1995) and fMRI studies (Dobbins et al., 2003; Henson et al., 1999) have suggested that parietal activity may be specific to (or preferential for) recollection. If this possibility is correct, then BA 40/39 should be more active for REMEMBER than for KNOW, and KNOW should be similar to NEW.

Time courses for each condition in each region, whether derived from exploratory (see Whole-brain exploratory analyses) or hypothesis-driven analyses, were computed by subtracting the hemodynamic response for the selectively averaged FIX condition at each of the eight time points (identical to Buckner et al., 1998b; Wheeler and Buckner, 2003; Wheeler et al., 2000). Peak response magnitude estimates were typically calculated by subtracting the mean signal magnitude at times 0 and 16.52 s (representing the baseline) from the mean signal magnitude at times 4.72 and 7.08 s. This magnitude estimation procedure assumes a relatively simple hemodynamic response model and is stable even when the peak magnitudes approach zero. However, peak hemodynamic responses for the KNOW, MISS, and CR conditions in BA 40/39 were delayed relative to REMEMBER (see Fig. 2C), so peak estimate time points for these three conditions were shifted, post hoc, to 7.08 and 9.44 s to adequately capture the peak response values. This latter procedure was verified using two additional estimation procedures. In one procedure, magnitude estimates were derived for all conditions using peak time points of 4.72, 7.08, and 9.44 s (with baseline subtracted). In another procedure, absolute difference magnitudes were computed by summing the squared difference, from baseline, for each non-baseline time point. The magnitude estimates for each subject were entered into a mixed-effects model, treating subjects as a random effect, and specific comparisons were made using t tests.

Whole-brain exploratory analyses

Exploratory analyses were carried out independently of a priori hypotheses. These analyses allow a full exploration of the functional data, but are less powerful than directed region-based analyses because they require correction for multiple comparisons and do not benefit (beyond smoothing) from signal averaging across voxels within a region. Statistical activation maps were constructed for each condition on a voxel-by-voxel basis using a t statistic in which contrasts of interest were regressed against a set of seven time-lagged (offset by 1 s, beginning at time 0 s) γ functions that approximate the range of typical hemodynamic responses (Boynton et al., 1996; Dale and Buckner, 1997; Schacter et al., 1997). Regions of activation were identified using a significance threshold of $P < 0.005$ and 19 or more contiguous significant voxels (152 mm^3). This threshold, while more lenient than used previously (Buckner et al., 1998b; Konishi et al., 2001), yields few false-positive findings in control data sets. However, because of these lenient criteria, observations stemming from the exploratory analyses should be considered tentative. Critical results that are interpreted in a theoretical context arise from the conservative hypothesis-driven regional analyses.

Results

Behavioral results

Accuracy and response time (RT) data are listed in Table 1. Subjects correctly recognized 62% of the old items studied with pictures (Table 1). Of those correctly recognized old items, 63% were identified as having been remembered and 37% known. Subjects guessed or made no response on 8% of old and 11% of new items, and correctly rejected 59% of the new lures. FA-REM, FA-KNOW, and GUESS trials with no response were not included in subsequent imaging analyses. Two-tailed t tests showed that subjects were not simply guessing when making both remember [REMEMBER > FA-REM; $t(19) = 14.66$, $P < 0.0001$] and know [KNOW > FA-KNOW; $t(19) = 3.21$, $P < 0.005$] responses.

Mean REMEMBER responses were faster than KNOW, MISS, and CR responses, as revealed by a single factor ANOVA [$F(3,57) = 32.84$, $P < 0.0001$] and subsequent post hoc t tests (all $P < 0.0001$). Most REMEMBER responses were made well before KNOW, MISS, and CR (Fig. 1; note that the MISS RT distribution, though not shown, was similar to the KNOW distribution). Across all trials, 79% of REMEMBER responses were made within 2 s of a possible 3.54 s response window, compared to only 41% KNOW, 48% MISS, and 55% CR. The RT data indicate that, with respect to studied items, when subjects recollected details of the study episode, responses were relatively fast. In absence of recollection, the decision process was extended as subjects likely used the available time to exhaustively search for recollective details. This pattern was present with respect to new items as well. Responses to FA-REM items were faster than to FA-KNOW [$t(19) = 3.64$, $P < 0.005$], so even when subjects were incorrect, they were faster when making a remember than a know response. Overall, the behavioral data, combined with participant feedback, indicate that REMEMBER responses associate with a relatively short search process that resulted in the retrieval of recollective content, while KNOW responses were associated with a more extended search process that resulted in a recognition decision likely based on familiarity.

Left parietal cortex, near intraparietal sulcus, associates with both remember and know responses

Left parietal cortex near BA 40/39 often increases activity for old relative to new items (Donaldson et al., 2001b; Habib and Lepage, 1999; Henson et al., 1999; Konishi et al., 2000; McDermott et al., 2000; Wheeler and Buckner, 2003). In the current experiment, BA 40/39 was more active for REMEMBER and

KNOW than for MISS and CR, but did not modulate as a function of the subjective experience of recognition (see Figs. 2A–C). Specifically, the REMEMBER condition was associated with a significantly greater response than MISS [$t(19) = 3.97$, $P < 0.001$] and CR [$t(19) = 4.26$, $P < 0.001$]. Similarly, the KNOW condition was also greater than MISS [$t(19) = 2.95$, $P < 0.01$] and CR [$t(19) = 3.55$, $P < 0.005$] conditions. There was, however, no significant difference in activity between REMEMBER and KNOW [$t(19) = 0.16$], or between MISS and CR [$t(19) = -0.24$], indicating that, independent of the subjective experience associated with retrieval, the BA 40/39 intraparietal region increased activity during correct identification of old items. All conditions were associated with an increased response relative to FIX baseline (all $P < 0.01$).

To test the robustness of these effects, magnitudes were computed using two additional magnitude estimation procedures (see Methods). Estimating magnitudes for all conditions with peak time points at 4.72, 7.08, and 9.44 s (and correcting for baseline) revealed the same pattern of results for REMEMBER, KNOW, MISS, and CR conditions (0.13%, 0.12%, 0.05%, 0.05% signal change, respectively). The difference between REMEMBER and KNOW was not significant [$t(19) = .63$]. Estimating magnitudes by summing the squared differences from baseline (for all non-baseline time points) also revealed the same pattern of results (0.11%, 0.14%, 0.06%, 0.05% signal change). Again, the difference between REMEMBER and KNOW was not significant [$t(19) = -1.17$].

Note that the effects found in left intraparietal cortex were also present when all trial onsets were time-locked with stimulus onset (rather than with behavioral response), indicating that the results were not an artifact of event coding. The KNOW response (0.14% signal change) was slightly reduced relative to REMEMBER (0.16%), but the difference was not significant [$t(19) = 1.04$]. The MISS (0.07%) and CR (0.07%) conditions were also not different [$t(19) = 0.42$] and both were associated with less activity than REMEMBER and KNOW (all $P < 0.05$).

Left inferior temporal cortex selectively associates with remembering

A subset of left inferior temporal cortex, which has been associated with perception and retrieval of visual object information (Köhler et al., 1998; Owen et al., 1996; Wheeler and Buckner, 2003; Wheeler et al., 2000), showed selective modulation depending on the subjective experience of recognition. A left anterior fusiform region near BA 20, which has previously been found to reactivate during retrieval of visual object information (Wheeler and Buckner, 2003), was more active for REMEMBER than for KNOW [$t(19) = 3.26$, $P < 0.005$], MISS [$t(19) = 2.39$, $P < 0.05$], and CR [$t(19) =$

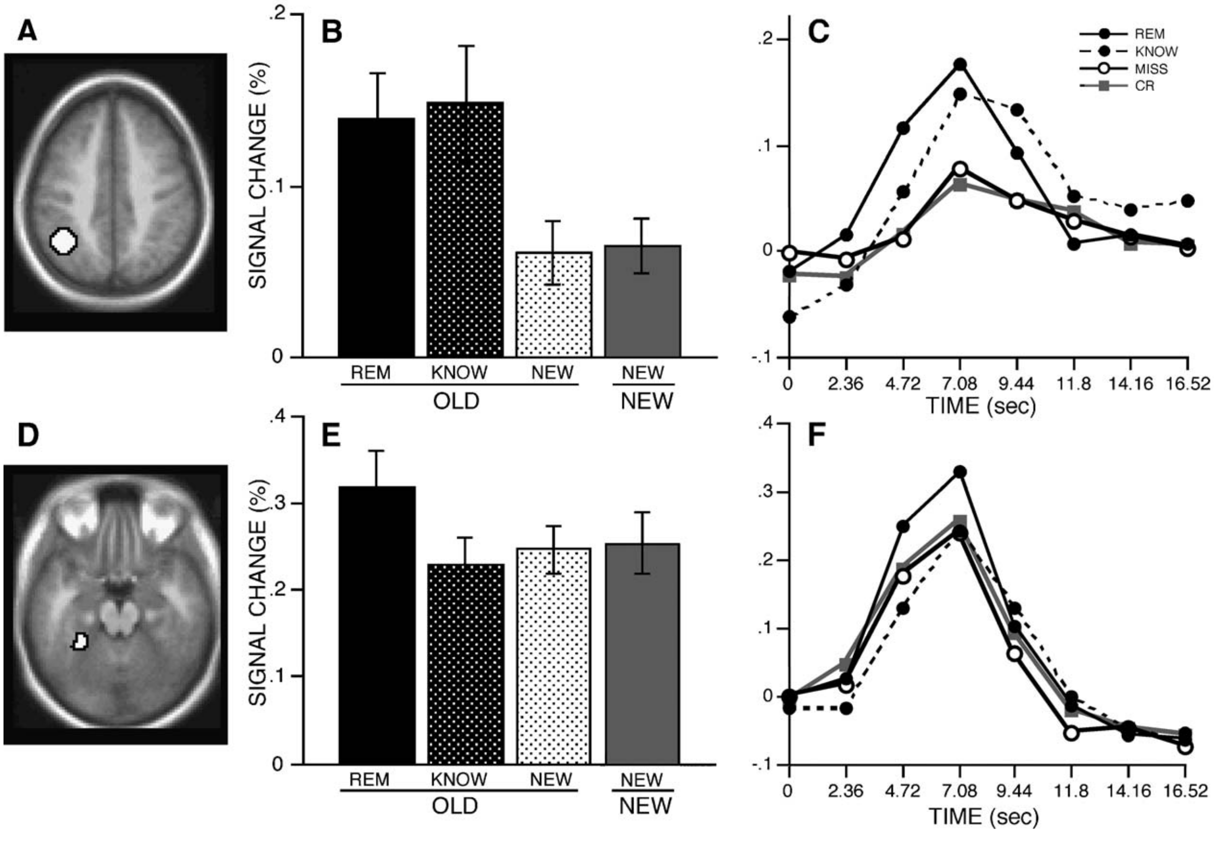

Fig. 2. Dissociated activity patterns that are common and distinct between REMEMBER and KNOW responses. (A) A horizontal slice at $z = 36$ shows a cross section of the BA 40/39 region used in the hypothesis-driven analyses, overlaid onto the average anatomical image. (B) Signal magnitude estimates in percentage of signal change for BA 40/39 across REMEMBER, KNOW, MISS (old item, new response) and CR (new item, new response) conditions. See Methods for magnitude estimation procedures. Percentage of signal change is relative to the FIX baseline. Error bars represent the standard error of the mean. (C) BOLD time courses over eight time points for each response condition. (D, E, F) Analogous data presented for the left anterior fusiform region. Horizontal slice at $z = 20$.

2.15, $P < 0.05$] responses (Figs. 2D–F). No differences in activity were found among KNOW, MISS, and CR responses (all $P > 0.38$). As in prior studies, BA 20 was presumably also active during the processing of visual word cues during the test because activity increased for all conditions relative to the FIX baseline (all $P <$ 0.0001) (similar to Buckner et al., 2000; Wheeler and Buckner, 2003). REMEMBER responses thus showed increased activity in BA 20, above that attributable to the word cues, when recognition decisions were likely based on recollective content.

The effects found in left anterior fusiform gyrus were also present when all trial onsets were time-locked with stimulus onset, with the REMEMBER condition (0.31%) associated with more activity than KNOW [0.18%; $t(19) = 4.44$, $P < 0.0005$], MISS [0.22%; $t(19) = 4.32$, $P < 0.0005$], and CR [0.24%; $t(19) = 2.28$, $P < 0.05$] conditions. The difference between KNOW and CR conditions was reliable [$t(19) = -2.23$, $P < 0.05$].

Lateral inferior temporal cortex near the anterior occipital sulcus (approximate BA 19/37), which has also been associated with retrieval of visual object content, failed to significantly modulate across retrieval conditions in the current experiment (all $P > 0.05$; Figs. 3A–C).

Exploratory analyses: remembering and knowing

Direct comparison of REMEMBER and KNOW conditions showed that remembering was associated with increased activity in bilateral parietal cortex near BA 40, left inferior parietal cortex near BA 39, left middle frontal gyrus near BA 6/8, medial frontal gyrus near BA 9, left posterior cingulate gyrus, and bilateral insular/opercular cortex (Fig. 4A). Most of the regions more active for the REMEMBER condition were left-lateralized, with the notable exception of activations near the right hippocampal formation and the right anterior fusiform gyrus at or near BA 20 (Fig. 4A, $z = -20$), the latter of which may have been specifically associated with retrieved picture information (or other visual content supporting remembering). None of the activations in left fusiform gyrus met the region criteria selected for exploratory analyses (19 or more contiguous voxels at or above $P < 0.005$), but several activations were noted in the activation map at more lenient criteria (Fig. 4A, $z = -20$). The REMEMBER vs. KNOW comparison also revealed bilateral activity related to remembering in or near the hippocampus (Fig. 4A, $z = -12$). The REMEMBER condition was associated with less activity than KNOW in a region located near the right middle frontal gyrus (~BA 9; see Fig. 4B, $z = 28$).

Evidence for anatomic specificity within left parietal cortex

The comparison of REMEMBER and KNOW identified two left-lateralized regions of parietal cortex that were relatively more active for the REMEMBER condition (see Fig. 4A, $z = 36, 28$). These regions were lateral and posterior to the left parietal BA 40/39 region used in the hypothesis-driven analyses (see Fig. 2A), but there appeared to be at least a partial overlap. This observation was intriguing given the earlier finding that the a priori defined parietal region increased activity for REMEMBER and KNOW responses. The three regions were projected onto both flattened and partially inflated representations of the left hemisphere cortical surface for improved visualization (Fig. 5A) (see Drury et al., 1996; Van Essen et al., 2001a,b; see also projection procedures as described in Wheeler and Buckner, 2003, and http://brainmap.wustl.edu/caret). To further characterize these regions, time courses of activity were extracted from individual subjects and analyzed. The more lateral (lateral parietal: LATPAR: $x = -51$, $y = -51$, $z = 38$) and more posterior (posterior parietal: POSTPAR: $x = -43$, $y = -67$, $z = 40$) regions exhibited different patterns of activity than BA 40/39 (Figs. 5C, D). BA 40/39, as noted, shows differential activity for REMEMBER and KNOW responses relative to MISS and CR responses. In addition, responses in the BA 40/39 region, for all conditions, were increased relative to FIX (Fig. 5B). By contrast, activity in LATPAR and POSTPAR showed a selective increase for REMEMBER responses over all other response types. Moreover, relative to the FIX condition, KNOW, MISS, and CR responses decreased below baseline.

To compare the REMEMBER and KNOW conditions across regions, magnitude estimates were obtained for the both conditions in each region, using response-locked data and peak estimates as described in Methods (shifted for KNOW in BA 40/39). Magnitudes were entered into a 2 (Condition) × 3 (Region) ANOVA, which showed significant main effects of Region [$F(2,38) = 30.23$, $P < 0.0001$] and Condition [$F(1,19) = 9.21$, $P < 0.01$] and a significant Region × Condition interaction [$F(2,38) = 14.07$, $P <$ 0.0001], indicating that the pattern of activity related to the subjective experience of recognition was different across the three regions. Note that results of this analysis should be considered with

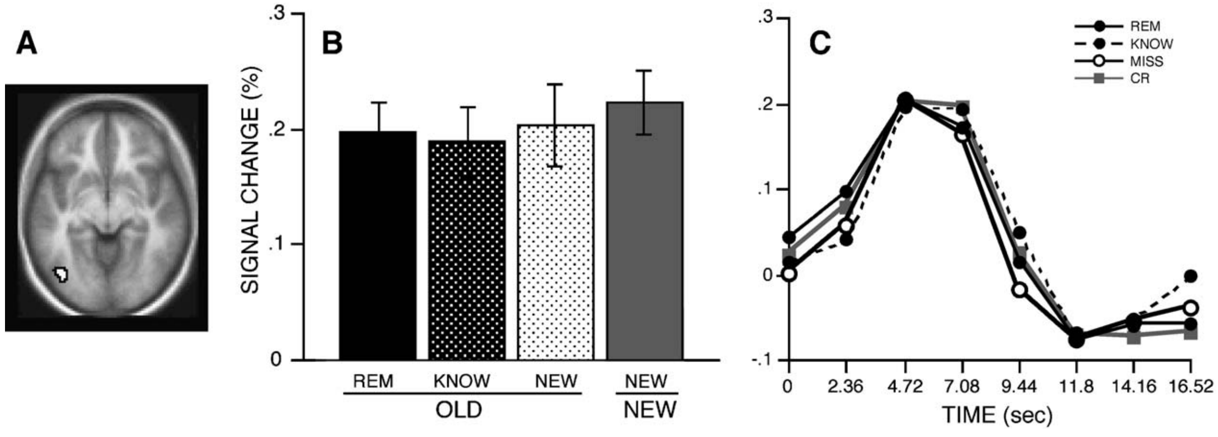

Fig. 3. Anterior occipital sulcus (at or near BA 19/37) BOLD responses sorted by response condition. Format is similar to Fig. 2. Horizontal section at $z = -6$.

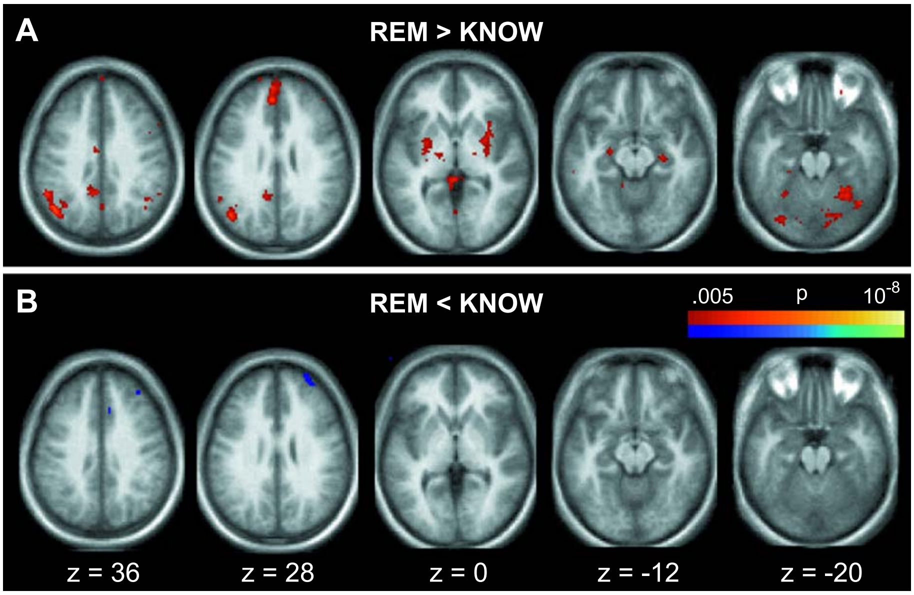

Fig. 4. Statistical activation maps show results from the exploratory analyses. (A) Regions that were greater for REMEMBER than KNOW (REM > KNOW), (B) Regions that were less for REMEMBER than for KNOW (REM < KNOW). Significance of activation is denoted by the color bar. Activations are presented over a backdrop of the average structural (T1-weighted) images. Five slices aligned to the AC-PC plane of the are presented with *z* coordinates shown at the bottom. R = right, *P* = level of significance.

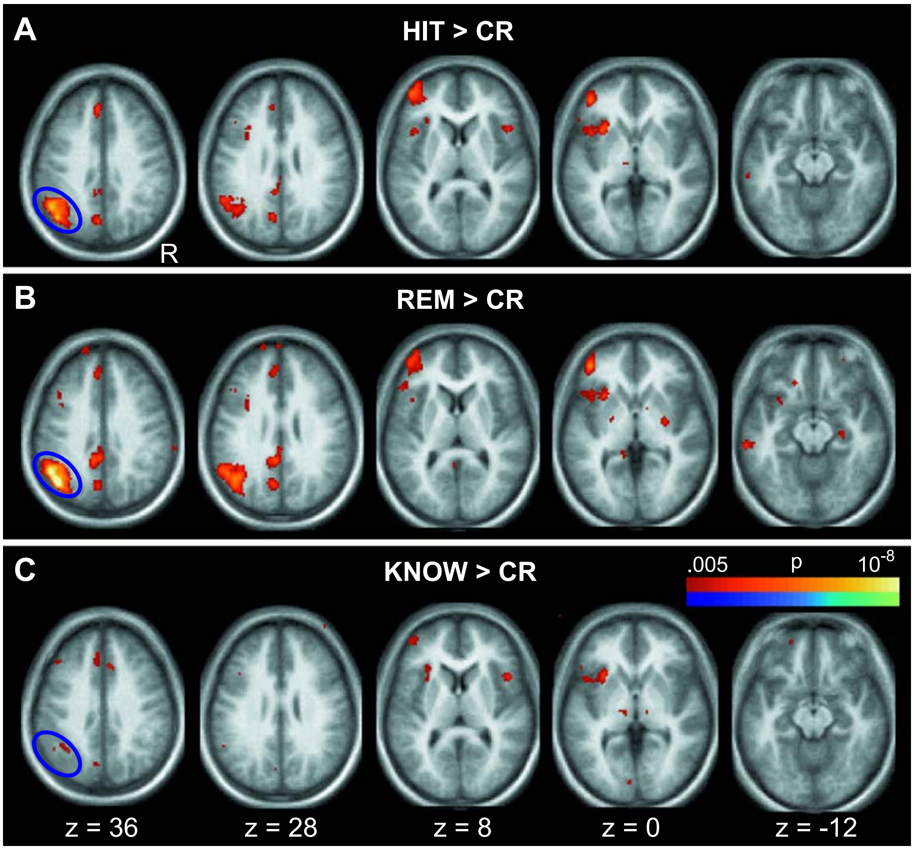

Fig. 6. Statistical activation maps show exploratory comparisons between (A) HITS and CR, (B) REMEMBER (REM) and CR, and (C) KNOW and CR. Format is similar to Fig. 4. Blue circles highlight activations in left parietal cortex. Note the differences in spatial topography of activations among the three comparisons.

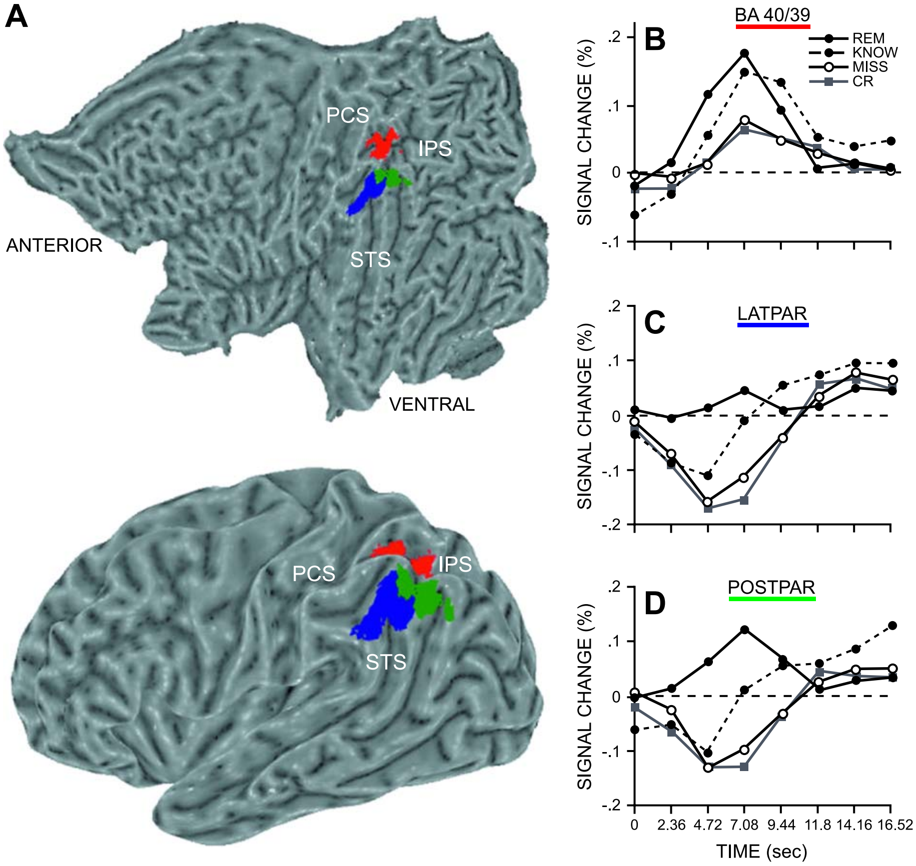

Fig. 5. Visualization of the functionally dissociated parietal regions identified by exploratory analysis. (A) Left parietal regions of interest are projected onto a flattened and an inflated lateral view of the left hemisphere. Darker shading indicates sulci, lighter shading indicates gyri. The BA 40/39 region from Konishi et al. (2000), shown in red, can be seen near the anterior portion of the intraparietal sulcus (IPS). LATPAR, shown in blue, is lateral to BA 40/39 and located near the supramarginal gyrus. POSTPAR, shown in green, lies posterior to, and partially overlaps, LATPAR. (B–D) Graphs show time courses for each response condition in each region (B, BA 40/39; C, LATPAR; D, POSTPAR). Color-coded lines under each region name represent the color of the region in A. Legend is shown in B, REM = REMEMBER, STS = superior temporal sulcus, PCS = postcentral sulcus.

caution because two of the three regions were defined by a direct comparison between the REMEMBER and KNOW conditions, and thus the analysis is somewhat biased.

Thus, the functional response properties of these parietal regions differed along two dimensions. First, BA 40/39 was not selective for remembering but rather increased activity for KNOW responses as well. By contrast, LATPAR and POSTPAR selectively modulated for only REMEMBER responses. Second, hemodynamic responses in BA 40/39 were all at or above baseline fixation. Responses in LATPAR and POSTPAR, however, were decreased below baseline, characteristic of these regions' behavior in many studies (e.g., Shulman et al., 1997a). Note also that the increased response for the REMEMBER condition in LATPAR and POSTPAR was relative to decreases for the other conditions.

Exploratory analyses: hits and correct rejections

To identify regions associated with successful retrieval of previously studied information, REMEMBER and KNOW responses were combined (hits) and compared to CRs. This comparison showed predominantly left-lateralized activations in inferior and lateral parietal cortex near the supramarginal gyrus (~BA 40/39), middle frontal gyrus (~BA 6), medial frontal gyrus (~BA 6/8), inferior frontal gyrus near the junction of BA 47/10, insular cortex near frontal operculum, and medial parietal cortex at or near BA 7 (Fig. 6A). This pattern of activations is consistent with previous reports on recognition memory (e.g., Donaldson et al., 2001b; Habib and Lepage, 1999; Henson et al., 1999; Konishi et al., 2000; McDermott et al., 2000; Wheeler and Buckner, 2003).

Furthermore, activations related to REMEMBER and KNOW, when analyzed independently, were associated with both common and different regions of activation, relative to CR. Regions showing relatively greater activity for KNOW than CR were located in frontal (BA 8, 10, 6, and 44) and left parietal cortex (Fig. 6C), while regions associated with REMEMBER were more widespread, with prominent activations in left frontal, left parietal, left temporal, and insular cortex, and thalamus (Fig. 6B). Most regions that were more active for KNOW than for CR were also more active for REMEMBER than CR, perhaps suggesting that responses based on nonrecollective processes were a subset of those associated with remember responses.

Discussion

The primary findings in this experiment were that remembering and knowing both activated a left intraparietal region that associates with the perception or decision that information is old, and remembering additionally activated content-based anterior fusiform regions that associate with processing visual object information. More specifically, items correctly identified as old corresponded with increased activity in left intraparietal cortex at or near BA 40/39, relative to missed old and correctly rejected new items. This region has been repeatedly associated with old responses in recognition paradigms (Donaldson et al., 2001b; Düzel et al., 1997; Habib and Lepage, 1999; Henson et al., 1999; Konishi et al., 2000; McDermott et al., 2000; Wheeler and Buckner, 2003). Remembering, however, was additionally accompanied by increased activity in bilateral anterior fusiform gyrus near BA 20, which has been associated with both the perception (Haxby et al., 1994; Kourtzi and Kanwisher, 2001; Maccotta and Buckner, 2002; Malach et al., 1995) and retrieval (Ishai et al., 2000; O'Craven and Kanwisher, 2000; Wheeler and Buckner, 2003) of visual object information. While it was not possible to directly test the level of activity for SND trials in the left BA 20 region, previous studies (e.g., Wheeler and Buckner, 2003) have shown that activity in inferior temporal cortex is greater during picture retrieval than sound retrieval. The results indicate that remembering is associated with concurrent activity in parietal regions that might associate with a general signal or decision that information has been previously experienced, and in 'content' regions that are specialized to process particular types of information. Knowing, while also associated with increased activity in a left intraparietal region, was not associated with increased activity (relative to new items) in regions that process visual object content. We also, unexpectedly, observed functional dissociation among regions within left parietal cortex. These unexpected findings are discussed first, followed by a discussion of the implications of the results to understanding components of remembering.

Left parietal cortex contains functionally distinct regions

Three regions with different patterns of activity were identified in left parietal cortex. One anterior and medial region (near BA 40/39) (Konishi et al., 2000) increased activity for both REMEMBER and KNOW conditions while two additional, likely anatomically separate regions, responded preferentially to REMEMBER responses. Moreover, these separate parietal regions also showed different overall levels of activation relative to the FIX baseline. Both of the parietal regions that preferentially responded to REMEMBER judgments did so relative to activity reductions in the other retrieval conditions (see Fig. 5).

The extent to which LATPAR and POSTPAR comprise two (or more) distinct regions is unclear from the current data. However, determining an appropriate basis for segregating these regions will be critical because hemodynamic responses tend to be negative in some regions and positive in others, including several parietal regions that show prominent negative hemodynamic responses across numerous task forms (Shulman et al., 1997a). As an example of where these functional-anatomic dissociations may be relevant, in one recent memory experiment (see Figs. 3B, C in Donaldson et al., 2001b), one parietal region appears to overlap both the LATPAR and the more medial intraparietal BA 40/39 region. However, another parietal region, similar in location to POSTPAR, was analyzed separately. It is unclear at this time which grouping yields an accurate assessment of regional activity.

Henson et al. (1999) reported similar parietal findings from a remember/know experiment using word stimuli. Their remember/know comparison revealed activity in left parietal cortex (peak, $x = -42$, $y = -72$, $z = 39$), which roughly corresponds with our LATPAR and POSTPAR regions, and was more active during remembering than knowing. A more medial and anterior activation identified in the Henson et al. (1999) remember-new comparison (peak, $x = -33$, $y = -60$, $z = 45$) roughly corresponds to our BA 40/39 region and was more active for remember and know responses than new responses. In a different experiment, Maril et al. (2003) identified a left parietal region near our BA 40/39 region (with peak voxel at $x = -45$, $y = -54$, $z = 45$) that was active during both 'knowing' (the analogous remember condition in that experiment) and 'feeling-of-knowing' (the know condition in that experiment) responses. In accord with the results here, left parietal activity was greater for both correct 'know' and 'feeling-of-knowing' items than for items that received a 'don't know' response.

Collectively, the results are consistent with the hypothesis that activity within intraparietal BA 40/39 aligns, in some manner, with a general signal that information is old or with post-identification and decision processes associated with old items (Donaldson et al., 2001b; Wheeler and Buckner, 2003). The results additionally suggest that more lateral and posterior regions modulate with a distinct pattern that correlates selectively with remembering in the present study. These results may explain why some ERP experiments have found differential activity over left parietal scalp electrodes for recollection-based than for familiarity-based responses (e.g., Donaldson and Rugg, 1998; Smith, 1993; Wilding and Rugg, 1996; for review, see Rugg and Allan, 2000). Considering only relative differences between remembering and non-remembering conditions, remembering was associated with increased activity in multiple parietal regions (i.e., LATPAR, POSTPAR, BA 40/39 regions in the present study), whereas knowing was associated with *increased* activity in one parietal region (i.e., BA 40/39). Scalp potentials recorded by ERP may reflect the additive signal across these different regions. At issue as well is how to consolidate findings of a parietal contribution to mnemonic decisions with findings from a wide variety of experiments using other tasks, including saccade and attention tasks, that also associate with parietal cortex (e.g., Astafiev et al., 2003; Connolly et al., 2002; Culham and Kanwisher, 2001; Kanwisher and Wojciulik, 2000; Posner and Petersen, 1990; Posner et al., 1984; Shulman et al., 1997a, 1999, 2003).

Comparison of remember and know responses

Direct comparison of REMEMBER and KNOW conditions revealed regions more associated with remembering than knowing. These regions, for the most part, are consistent with regions identified in previous remember/know experiments (Eldridge et al., 2000; Henson et al., 1999). One important difference from earlier studies was that in this experiment, content-based regions could be selectively isolated because of the object-content instantiated at encoding. Bilateral anterior fusiform gyrus was more active during remembering than knowing (see Fig. 4A, $z = -20$), a difference likely due to the presence of trials in which subjects retrieved picture content to support remembering. Remembering was also associated with other regions of note, including bilateral activations at or near the hippocampus, a finding that has been previously reported (Eldridge et al., 2000).

Interestingly, the KNOW condition was associated with greater activity than REMEMBER in a region near right middle frontal gyrus (peak coordinate: $x = 29$, $y = 53$, $z = 28$; ~BA 9;

see Fig. 4B, $z = 28$). This region is located in dorsolateral prefrontal cortex (DLPFC) just anterior to a know > remember activation peak reported by Henson et al. (1999) and near the peak location of a right frontal activation reported by Eldridge et al. (2000). Right DLPFC might play a role in the active maintenance or manipulation of information, such as is commonly required in working memory paradigms (D'Esposito et al., 2000; Jonides et al., 1993; Owen, 1997; Petrides et al., 1995; Ranganath et al., 2003; Wagner, 1999). Participation in the KNOW condition may occur because of the extended decision processes, as suggested by the long response times. Alternatively, right DLPFC could play a role in post-retrieval monitoring (Burgess and Shallice, 1996; Henson et al., 1999; Nolde et al., 1998), such that additional monitoring is required when recollective evidence is lacking. Left frontal regions, which appear regularly in many different kinds of tasks, were also active in the present experiment but were not found to modulate as a function of the subjective experience of recognition memory. Taken together, these results suggest a role for specific frontal regions in controlled processes that generalize to decisions involving minimal recollective content.

Implications for theories of remembering

While a one-to-one correspondence between remember vs. know decisions and recollection vs. familiarity does not exist, know responses, on average, align more with familiarity-based recognition than remember responses (Henson et al., 1999; Yonelinas, 2001; Yonelinas and Jacoby, 1995). The present data can thus inform ideas about the relation between recollection and familiarity. The present results suggest that both bases for recognition share a common process that is reflected in activation within the left intraparietal sulcus. Perhaps activation of this region, or the network this region participates in, is sufficient to supply a perception that information is familiar, or responds following detection of familiarity. Prior data suggest activation of this region can occur rapidly and sometimes spontaneously to old items (Donaldson et al., 2001a; Koutstaal et al., 2001). Contrary to some conceptions regarding the independence of familiarity and recollection, this parietal signal also appears to correlate with recollection, suggesting at least a partially shared neural basis. Beyond their similarities, remember decisions also show distinct correlates that may selectively associate with recollection. In particular, the finding that remember decisions associate with activation of late visual regions makes intuitive sense given that the study context included associated visual objects.

Based on these observations, we speculatively propose that, although recollection and familiarity can be behaviorally (and sometimes neurally, see Düzel et al., 1997; Eldridge et al., 2000; Henson et al., 1999; Rugg et al., 2003; Wilding and Rugg, 1997) dissociated, they nonetheless share core, memory-relevant, processes in common. Theories of remembering should further explore, and perhaps emphasize, these commonalities. The data also suggest a fundamental way in which recollection may differ from familiarity, which may partially account for the several notable dissociations that have been obtained behaviorally. Remember decisions and, by assumption, recollection-based retrieval decisions, depend on selective reactivation of brain regions supplying retrieval content. Such a qualitative difference is in line with notions that remember decisions are not simply the reflection of a particularly confident event, or of higher values that surpass some decision threshold, or of a single-process continuum with familiarity-based decisions. Rather, remembering appears to involve distinct cortical processes that supply retrieved content and, in combination with other still-to-be understood components, may serve to underlie the qualitative differences that emerge in recollection-based retrieval events.

Acknowledgments

We thank Larry Jacoby, Kathleen McDermott, Luigi Maccotta, Fran Miezin, Steve Petersen, Jeff Toth, Endel Tulving, and Katerina Velanova for helpful comments, assistance, and advice. Denise Head assisted with data collection. Avi Snyder helped develop post-processing software and Tom Conturo and Erbil Akbudak supplied imaging sequences. David Van Essen provided Caret software. Two anonymous reviewers provided helpful suggestions. This research was supported by the Howard Hughes Medical Institute, the James S. McDonnell Foundation, and the National Institute of Mental Health (MH57506).

References

Astafiev, S.V., Shulman, G.L., Stanley, C.M., Snyder, A.Z., Van Essen, D.C., Corbetta, M., 2003. Functional organization of human intraparietal and frontal cortex for attending, looking, and pointing. J. Neurosci. 23, 4689–4699.

Bandettini, P.A., Jesmanowicz, A., Wong, E.C., Hyde, J.S., 1993. Processing strategies for time-course data sets in functional MRI of the human brain. Magn. Reson. Med. 30, 161–173.

Bartlett, F.C., 1932. Remembering: A Study in Experimental and Social Psychology Cambridge Univ. Press, Cambridge.

Boynton, G.M., Engel, S.A., Glover, G.H., Heeger, D.J., 1996. Linear systems analysis of functional magnetic resonance imaging in human V1. J. Neurosci. 16, 4207–4221.

Buckner, R.L., Wheeler, M.E., 2001. The cognitive neuroscience of remembering. Nat. Rev., Neurosci. 2, 624–634.

Buckner, R.L., Koutstaal, W., Schacter, D.L., Dale, A.M., Rotte, M.R., Rosen, B.R., 1998a. Functional-anatomic study of episodic retrieval: II. Selective averaging of event-related fMRI trials to test the retrieval success hypothesis. NeuroImage 7, 163–175.

Buckner, R.L., Goodman, J., Burock, M., Rotte, M., Koutstaal, M., Schacter, D.L., Rosen, B., Dale, A.M., 1998b. Functional-anatomic correlates of object priming in humans revealed by rapid presentation event-related fMRI. Neuron 20, 285–296.

Buckner, R.L., Koutstaal, W., Schacter, D.L., Rosen, B.R., 2000. Functional MRI evidence for a role of frontal and inferior temporal cortex in amodal components of priming. Brain 123, 620–640.

Burgess, P.W., Shallice, T., 1996. Confabulation and the control of recollection. Memory 4, 359–411.

Cabeza, R., Nyberg, L., 2000. Imaging cognition II: an empirical review of 275 PET and fMRI studies. J. Cogn. Neurosci. 12, 1–47.

Cansino, S., Maquet, P., Dolan, R.J., Rugg, M.D., 2002. Brain activity underlying encoding and retrieval of source memory. Cereb. Cortex 12, 1048–1056.

Cohen, J.D., MacWhinney, B., Flatt, M., Provost, J., 1993. PsyScope: a new graphic interactive environment for designing psychology experiments. Behav. Res. Meth. Instrum. Comput. 25, 257–271.

Connolly, J.D., Goodale, M.A., Menon, R.S., Munoz, D.P., 2002. Human fMRI evidence for the neural correlates of preparatory set. Nat. Neurosci. 5, 1345–1352.

Conturo, T.E., McKinstry, R.C., Akbudak, E., Snyder, A.Z., Yang, T.Z., Raichle, M.E., 1996. Sensitivity optimization and experimental design in functional magnetic resonance imaging. Abstr. - Soc. Neurosci. 22, 7.

Culham, J.C., Kanwisher, N.G., 2001. Neuroimaging of cognitive functions in human parietal cortex. Curr. Opin. Neurobiol. 11, 157–163.

Dale, A.M., Buckner, R.L., 1997. Selective averaging of rapidly presented individual trials using fMRI. Hum. Brain Mapp. 5, 329–340.

Desgranges, B., Braon, J.C., Eustache, F., 1998. The functional neuroanatomy of episodic memory: the role of the frontal lobes, the hippocampal formation, and other areas. NeuroImage 8, 198–213.

Desimone, R., Miller, E.K., Chelazzi, L., Lueschow, A., 1995. Multiple memory systems in the visual cortex. In: Gazzaniga, M.S. (Ed.), The Cognitive Neurosciences. MIT Press, Cambridge, MA, pp. 475–486.

D'Esposito, M., Postle, B.R., Rypma, B., 2000. Prefrontal cortical contributions to working memory: evidence from event-related fMRI studies. Exp. Brain Res. 133, 3–11.

Dobbins, I.G., Foley, H., Schacter, D.L., Wagner, A.D., 2002. Executive control during episodic retrieval: multiple prefrontal processes subserve source memory. Neuron 35, 989–996.

Dobbins, I.G., Rice, H.J., Wagner, A.D., Schacter, D.L., 2003. Memory orientation and success: separable neurocognitive components underlying episodic recognition. Neuropsychologia 41, 318–333.

Donaldson, D.I., Rugg, M.D., 1998. Recognition memory for new associations: electrophysiological evidence for the role of recollection. Neuropsychologia 36, 377–395.

Donaldson, D.I., Petersen, S.E., Buckner, R.L., 2001a. Dissociating memory retrieval processes using fMRI: evidence that priming does not support recognition memory. Neuron 31, 1047–1059.

Donaldson, D.I., Petersen, S.E., Ollinger, J.M., Buckner, R.L., 2001b. Dissociating state and item components of recognition memory using fMRI. NeuroImage 13, 129–142.

Drury, H.A., Van Essen, D.C., Anderson, C.H., Lee, C.W., Coogan, T.A., Lewis, J.W., 1996. Computerized mappings of the cerebral cortex. A multiresolution flattening method and a surface-based coordinate system. J. Cogn. Neurosci. 8, 1–28.

Düzel, E., Yonelinas, A.P., Mangun, G.R., Heinze, H.J., Tulving, E., 1997. Event-related brain potential correlates of two states of conscious awareness in memory. Proc. Natl. Acad. Sci. U. S. A. 94, 5973–5978.

Eldridge, L.L., Knowlton, B.J., Furmanski, C.S., Bookheimer, S.Y., Engel, S.A., 2000. Remembering episodes: a selective role for the hippocampus during retrieval. Nat. Neurosci. 3, 1149–1152.

Farah, M.J., 1989. The neural basis of mental imagery. Trends Neurosci. 12, 395–399.

Francis, W.N., Kucera, H., 1982. Frequency Analysis of English Usage: Lexicon and Grammar. Houghton Mifflin Company, Boston.

Gardiner, J.M., Java, R.I., 1993. Recognising and remembering. In: Collins, A., Gathercole, S.E., Conway, M.A., Morris, P.E. (Eds.), Theories of Memory. Erlbaum, Hillsdale, NJ, pp. 163–188.

Gardiner, J.M., Richardson-Klavehn, A., 2000. Remembering and knowing. In: Tulving, E., Craik, F.I.M. (Eds.), The Oxford Handbook of Memory. Oxford Univ. Press, New York, pp. 229–244.

Gardiner, J.M., Ramponi, C., Richardson-Klavehn, A., 1998. Experiences of remembering, knowing, and guessing. Conscious. Cogn. 7, 1–26.

Gardiner, J.M., Ramponi, C., Richardson-Klavehn, A., 2002. Recognition memory and decision processes: a meta-analysis of remember, know, and guess responses. Memory 10, 83–98.

Habib, R., Lepage, M., 1999. Novelty assessment in the brain. In: Tulving, E. (Ed.), Memory, Consciousness, and the Brain. Psychology Press, Philadelphia, pp. 265–277.

Haxby, J.V., Horwitz, B., Ungerleider, L.G., Maisog, J.M., Pietrini, P., Grady, C.L., 1994. The functional organization of human extrastriate cortex: a PET-rCBF study of selective attention to faces and locations. J. Neurosci. 14, 6336–6353.

Henson, R.N., Rugg, M.D., Shallice, T., Josephs, O., Dolan, R.J., 1999. Recollection and familiarity in recognition memory: an event-related functional magnetic resonance imaging study. J. Neurosci. 19, 3962–3972.

Ishai, A., Ungerleider, L.G., Haxby, J.V., 2000. Distributed neural systems for the generation of visual images. Neuron 28, 979–990.

Jacoby, L.L., 1991. A process dissociation framework: separating automatic from intentional uses of memory. J. Mem. Lang. 30, 513–541.

James, W., 1890. The Principles of Psychology. Henry Holt and Company, New York.

Jonides, J., Smith, E.E., Koeppe, R.A., Awh, E., Minoshima, S., Mintun, M.A., 1993. Spatial working memory in humans as revealed by PET. Nature 363, 623–625.

Josephs, O., Turner, R., Friston, K., 1997. Event-related fMRI. Hum. Brain Mapp. 5, 243–248.

Kanwisher, N., Wojciulik, E., 2000. Visual attention: insights from brain imaging. Nat. Rev., Neurosci. 1, 91–100.

Kastner, S., Pinsk, M.A., De Weerd, P., Desimone, R., Ungerleider, L.G., 1999. Increased activity in human visual cortex during directed attention in the absence of visual stimulation. Neuron 22, 751–761.

Köhler, S., Moscovitch, M., Winocur, G., Houle, S., McIntosh, A.R., 1998. Networks of domain-specific and general regions involved in episodic memory for spatial location and object identity. Neuropsychologia 36, 129–142.

Konishi, S., Wheeler, M.E., Donaldson, D.I., Buckner, R.L., 2000. Neural correlates of episodic retrieval success. NeuroImage 12, 276–286.

Konishi, S., Donaldson, D.I., Buckner, R.L., 2001. Transient activation during block transition. NeuroImage 13, 364–374.

Kosslyn, S.M., Alpert, N.M., Thompson, W.L., Maljkovic, V., Weise, S.B., Chabris, C.F., Hamilton, S.E., Rauch, S.L., Buonanno, F.S., 1993. Visual mental imagery activates topographically organized visual cortex: PET investigations. J. Cogn. Neurosci. 5, 263–287.

Kosslyn, S.M., Thompson, W.L., Kim, I.J., Alpert, N.M., 1995. Topographical representations of mental images in primary visual cortex. Nature 378, 496–498.

Kourtzi, Z., Kanwisher, N., 2001. Representation of perceived object shape by the human lateral occipital complex. Science 293, 1506–1509.

Koutstaal, W., Wagner, A.D., Rotte, M., Maril, A., Buckner, R.L., Schacter, D.L., 2001. Perceptual specificity in visual object priming: functional magnetic resonance imaging evidence for a laterality difference in fusiform cortex. Neuropsychologia 39, 184–199.

Kwong, K.K., Belliveau, J.W., Chesler, D.A., Goldberg, I.E., Weisskoff, R.M., Poncelet, B.P., Kennedy, D.N., Hoppel, B.E., Cohen, M.S., Turner, R., 1992. Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. Proc. Natl. Acad. Sci. U. S. A. 89, 5675–5679.

Maccotta, L., Buckner, R.L., 2002. Quantifying object processing and recognition in early and late visual areas. J. Cogn. Neurosci., 67 (Supplement).

Maccotta, L., Zacks, J.M., Buckner, R.L., 2001. Rapid self-paced event-related functional MRI: feasibility and implications of stimulus-versus response-locked timing. NeuroImage 14, 1105–1121.

Malach, R., Reppas, J.B., Benson, R.R., Kwong, K.K., Jiang, H., Kennedy, W.A., Ledden, P.J., Brady, T.J., Rosen, B.R., Tootell, R.B.H., 1995. Object-related activity revealed by functional magnetic resonance imaging in human occipital cortex. Proc. Natl. Acad. Sci. U. S. A. 92, 8135–8139.

Mandler, G., 1980. Recognizing: the judgment of previous occurrence. Psychol. Rev. 87, 252–271.

Maril, A., Simons, J.S., Mitchell, J.P., Schwartz, B.L., Schacter, D.L., 2003. Feeling-of-knowing in episodic memory: an event-related fMRI study. NeuroImage 18, 827–836.

McDermott, K.B., Jones, T.C., Petersen, S.E., Lageman, S.K., Roediger III, H.L., 2000. Retrieval success is accompanied by enhanced activation in anterior prefrontal cortex during recognition memory: an event-related fMRI study. J. Cogn. Neurosci. 12, 965–976.

Mellet, E., Tzourio-Mazoyer, N., Bricogne, S., Mazoyer, B., Kosslyn, S.M., Denis, M., 2000. Functional anatomy of high-resolution visual mental imagery. J. Cogn. Neurosci. 12, 98–109.

Miezin, F.M., Maccotta, L., Ollinger, J.M., Petersen, S.E., Buckner, R.L., 2000. Characterizing the hemodynamic response: effects of presentation rate, sampling procedure, and the possibility of ordering brain activity based on relative timing. NeuroImage 11, 735–759.

Miyashita, Y., 1988. Neuronal correlates of visual associative long-term memory in the primate temporal cortex. Nature 335, 817–820.

Moscovitch, D.A., McAndrews, M.P., 2002. Material-specific deficits in "remembering" in patients with unilateral temporal lobe epilepsy and excisions. Neuropsychologia 40, 1335–1342.

Nolde, S.F., Johnson, M.K., Raye, C.L., 1998. The role of prefrontal cortex during tests of episodic memory. Trends Cogn. Sci. 2, 399–406.

Nyberg, L., Habib, R., McIntosh, A.R., Tulving, E., 2000. Reactivation of encoding-related brain activity during memory retrieval. Proc. Natl. Acad. Sci. U. S. A. 97, 11120–11124.

Nyberg, L., Petersson, K.M., Nilsson, L.G., Sandblom, J., Åberg, C., Ingvar, M., 2001. Reactivation of motor brain areas during explicit memory for actions. NeuroImage 14, 521–528.

O'Craven, K.M., Kanwisher, N., 2000. Mental imagery of faces and places activates corresponding stimulus-specific brain regions. J. Cogn. Neurosci. 12, 1013–1023.

Ogawa, S., Tank, D.W., Menon, R., Ellerman, J.M., Kim, S.G., Merkle, H., Ugurbil, K., 1992. Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proc. Natl. Acad. Sci. U. S. A. 89, 5951–5955.

Owen, A.M., 1997. The functional organization of working memory processes within human lateral frontal cortex: the contribution of functional neuroimaging. Eur. J. Neurosci. 9, 1329–1339.

Owen, A.M., Milner, B., Petrides, M., Evans, A.C., 1996. Memory for object features versus memory for object location: a positron-emission tomography study of encoding and retrieval processes. Proc. Natl. Acad. Sci. U. S. A. 93, 9212–9217.

Petrides, M., Alivisatos, B., Evans, A.C., 1995. Functional activation of the human ventrolateral frontal cortex during mnemonic retrieval of verbal information. Proc. Natl. Acad. Sci. U. S. A. 92, 5803–5807.

Posner, M.I., Petersen, S.E., 1990. The attention system of the human brain. Annu. Rev. Neurosci. 13, 25–42.

Posner, M.I., Walker, J.A., Friedrich, F.J., Rafal, R.D., 1984. Effects of parietal injury on covert orienting of attention. J. Neurosci. 4, 1863–1874.

Rajaram, S., 1993. Remembering and knowing: two means of access to the personal past. Mem. Cogn. 21, 89–102.

Roland, P.E., Gulyás, B., 1995. Visual memory, visual imagery, and visual recognition of large field patterns by the human brain: functional anatomy by positron emission tomography. Cereb. Cortex 5, 79–93.

Ranganath, C., Johnson, M.K., D'Esposito, M., 2003. Prefrontal activity associated with working memory and episodic long-term memory. Neuropsychologia 41, 378–389.

Rösler, F., Heil, M., Hennighausen, E., 1995. Distinct cortical activation patterns during long-term memory retrieval of verbal, spatial, and color information. J. Cogn. Neurosci. 7, 51–65.

Rugg, M.D., Allan, K., 2000. Event-related potential studies of memory. In: Tulving, E., Craik, F.I.M. (Eds.), The Oxford Handbook of Memory. Oxford Univ. Press, New York, pp. 521–537.

Rugg, M.D., Schloerscheidt, A.M., Doyle, M.C., Cox, C.J.C., Patching, G.R., 1996. Event-related potentials and the recollection of associative information. Cogn. Brain Res. 4, 297–304.

Rugg, M.D., Otten, L.J., Henson, R.N., 2002. The neural basis of episodic memory: evidence from functional neuroimaging. Philos. Trans. R. Soc. Lond., B Biol. Sci. 357, 1097–1110.

Rugg, M.D., Henson, R.N.A., Robb, W.G.K., 2003. Neural correlates of retrieval processing in the prefrontal cortex during recognition and exclusion tasks. Neuropsychologia 41, 40–52.

Schacter, D.L., Wagner, A.D., 1999. Medial temporal lobe activations in fMRI and PET studies of episodic encoding and retrieval. Hippocampus 9, 7–24.

Schacter, D.L., Buckner, R.L., Koutstaal, W., Dale, A.M., Rosen, B.R., 1997. Late onset of anterior prefrontal activity during true and false recognition: an event-related fMRI study. NeuroImage 6, 259–269.

Shulman, G.L., Fiez, J.A., Corbetta, M., Buckner, R.L., Miezin, F.M., Raichle, M.E., Petersen, S.E., 1997a. Common blood flow changes across visual tasks: II. Decreases in cerebral cortex. J. Cogn. Neurosci. 9, 648–663.

Shulman, G.L., Corbetta, M., Buckner, R.L., Raichle, M.E., Fiez, J.A., Miezin, F.M., Petersen, S.E., 1997b. Top–down modulation of early visual cortex. Cereb. Cortex 7, 193–206.

Shulman, G.L., Ollinger, J.M., Akbudak, E., Conturo, T.E., Snyder, A.Z., Petersen, S.E., Corbetta, M., 1999. Areas involved in encoding and applying directional expectations to moving objects. J. Neurosci. 19, 9480–9496.

Shulman, G.L., McAvoy, M.P., Cowan, M.C., Astafiev, S.V., Tansy, A.P., d'Avossa, G., Corbetta, M., 2003. Quantitative analysis of attention and detection signals during visual search. J. Neurophysiol. 90, 3384–3397.

Smith, M.E., 1993. Neurophysiological manifestations of recollective experience during recognition memory judgments. J. Cogn. Neurosci. 5, 1–13.

Snyder, A.Z., 1996. Difference image versus ratio image error function forms in PET–PET realignment. In: Bailey, D., Jones, T. (Eds.), Quantification of brain function using PET. Academic Press, San Diego, pp. 131–137.

Talairach, J., Tournoux, P., 1988. Co-Planar Stereotaxic Atlas of The Human Brain. Thieme Medical Publishers, Inc, New York.

Tulving, E., 1983. Elements of Episodic Memory. Oxford Univ. Press, New York.

Tulving, E., 1985. Memory and consciousness. Can. Psychol. 26, 1–12.

Van Essen, D.C., Drury, H.A., Dickson, J., Harwell, J., Hanlon, D., Anderson, C.H., 2001a. An integrated software suite for surface-based analyses of cerebral cortex. J. Am. Med. Inform. Assoc. 8, 443–459.

Van Essen, D.C., Lewis, J.W., Drury, H.A., Hadjikhani, N., Tootell, R.B.H., Bakircioglu, M., Miller, M.I., 2001b. Mapping visual cortex in monkeys and humans using surface-based atlases. Vision Res. 41, 1359–1378.

Velanova, K., Jacoby, L.L., Wheeler, M.E., McAvoy, M.P., Petersen, S.E., Buckner, R.L., 2003. Functional-anatomic correlates of sustained and transient processing components engaged during controlled retrieval. J. Neurosci. 23, 8460–8470.

Wagner, A.D., 1999. Working memory contributions to human learning and remembering. Neuron 22, 19–22.

Wheeler, M.E., Buckner, R.L., 2003. Functional dissociation among components of remembering: control, perceived oldness, and content. J. Neurosci. 23, 3869–3880.

Wheeler, M.E., Petersen, S.E., Buckner, R.L., 2000. Memory's echo: vivid remembering reactivates sensory-specific cortex. Proc. Natl. Acad. Sci. U. S. A. 97, 11125–11129.

Wilding, E.L., Rugg, M.D., 1996. An event-related potential study of recognition memory with and without retrieval of source. Brain 119, 889–905.

Wilding, E.L., Rugg, M.D., 1997. Event-related potentials and the recognition memory exclusion task. Neuropsychologia 35, 119–128.

Wilding, E.L., Doyle, M.C., Rugg, M.D., 1995. Recognition memory with and without retrieval of context: an event-related potential study. Neuropsychologia 33, 743–767.

Yonelinas, A.P., 2001. Components of episodic memory: the contribution of recollection and familiarity. Philos. Trans. R. Soc. Lond., B 356, 1–12.

Yonelinas, A.P., 2002. The nature of recollection and familiarity: a review of 30 years of research. J. Mem. Lang. 46, 441–517.

Yonelinas, A.P., Jacoby, L.L., 1995. The relation between remembering and knowing as bases for recognition: effects of size congruency. J. Mem. Lang. 34, 622–643.

Zatorre, R.J., Halpern, A.R., Perry, D.W., Meyer, E., Evans, A.C., 1996. Hearing in the mind's ear: A PET investigation of musical imagery and perception. J. Cogn. Neurosci. 8, 29–46.