

## ORIGINAL ARTICLE

# Lower Parietal Encoding Activation Is Associated with Sharper Information and Better Memory

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## Abstract

Mean fMRI activation in ventral posterior parietal cortex (vPPC) during memory encoding often negatively predicts successful remembering. A popular interpretation of this phenomenon is that vPPC reflects “off-task” processing. However, recent fMRI studies considering distributed patterns of activity suggest that vPPC actively represents encoded material. Here, we assessed the relationships between pattern-based content representations in vPPC, mean activation in vPPC, and subsequent remembering. We analyzed data from two fMRI experiments where subjects studied then recalled word–face or word–scene associations. For each encoding trial, we measured 1) mean univariate activation within vPPC and 2) the strength of face/scene information as indexed by pattern analysis. Mean activation in vPPC negatively predicted subsequent remembering, but the strength of pattern-based information in the same vPPC voxels positively predicted later memory. Indeed, univariate amplitude averaged across vPPC voxels negatively correlated with pattern-based information strength. This dissociation reflected a tendency for univariate reductions to maximally occur in voxels that were not strongly tuned for the category of encoded stimuli. These results indicate that vPPC activity patterns reflect the content and quality of memory encoding and constitute a striking example of lower univariate activity corresponding to stronger pattern-based information.

**Key words:** angular gyrus, decoding, episodic memory, MVPA, subsequent memory

## Introduction

To identify brain regions that support the formation of new episodic memories, many fMRI studies have applied a simple analysis logic: brain regions that are important for forming new memories should be more active during the encoding of events that are subsequently remembered (recalled, retrieved, or recognized) relative to events that are subsequently forgotten (Brewer et al. 1998; Wagner et al. 1998). This analysis approach has been termed the “subsequent memory paradigm.” Regions that typically show increased activation during successful encoding (hereinafter positive subsequent memory effects) include medial temporal lobe structures and inferior aspects of prefrontal cortex (Fernández and Tendolkar 2001; Kim 2011). However, several brain regions consistently exhibit negative subsequent memory effects, where lower encoding activity predicts better remembering (Otten and Rugg 2001; Wagner and Davachi 2001; Daselaar

et al. 2004; Turk-Browne et al. 2006). Among those regions, ventral posterior parietal cortex (vPPC) has been of particular interest, since this area is typically more active during successful than failed memory retrieval (Daselaar et al. 2009; Kim et al. 2010; Vannini et al. 2011).

Several theoretical accounts have been proposed to explain the negative subsequent memory effect in vPPC. One explanation is based on dual-attention theory (Uncapher and Wagner 2009), which posits that vPPC activity tracks recruitment of reflexive or bottom-up attention, as opposed to dorsal PPC, whose activity tracks goal-directed or top-down attention (Corbetta and Shulman 2002). According to this hypothesis, higher activation in vPPC reflects bottom-up attention “captured” by task-irrelevant stimulus features or cognitive processes, which results in forgetting (Cabeza et al. 2008, 2012). Another way of interpreting the negative subsequent memory effect in vPPC is motivated by evidence that vPPC—and especially the angular gyrus (ANG)—is part

of the so-called default mode network (Shulman et al. 1997; Yeo et al. 2011), which consists of functionally interconnected brain regions that typically show enhanced activity during rest or baseline periods compared with active engagement in cognitive tasks (Buckner et al. 2008). Since the default mode network is considered to be involved in internally oriented cognition such as mind wandering (Mason et al. 2007; Christoff et al. 2009), greater activation in vPPC during encoding could reflect a lapse of attention to the external stimulus (Shulman et al. 2007), or, conversely, more processing of task-irrelevant internal thoughts. A related argument is that activity reductions in vPPC reflect successful reallocation of processing resources away from spontaneous thoughts or internal representations (Huijbers et al. 2012). From this perspective, lower vPPC activity signals “efficient suppression” of internal representations, which in turn facilitates processing/encoding of external stimuli (Vannini et al. 2013). Importantly, each of these accounts of negative subsequent memory effects in vPPC posit that higher activation in vPPC during encoding reflects allocation of mental and neural resources away from to-be-encoded events, which results in poorer remembering. Thus, vPPC is not typically thought to actively represent or process encoded information.

In contrast to earlier studies focusing only on univariate amplitude levels during encoding, several recent studies using multi-voxel pattern analysis (MVPA; Norman et al. 2006) suggest that vPPC activity patterns during encoding carry information about to-be-encoded material (Xue et al. 2012; Kuhl et al. 2013; Kuhl and Chun 2014). For example, during the encoding of faces and scenes, multi-voxel activity patterns in ANG reflect the visual category to which a stimulus belongs (Kuhl et al. 2013; Kuhl and Chun 2014), and the match between vPPC encoding and retrieval patterns has been associated with successful remembering (Kuhl and Chun 2014). Similarly, the consistency of stimulus-specific vPPC representations across multiple encoding trials, as measured by fMRI pattern analysis, predicts later remembering (Xue et al. 2012).

Collectively, the above results suggest a potential dissociation between univariate and pattern-based subsequent memory analyses: while univariate encoding activity in vPPC may negatively predict subsequent remembering, information reflected in vPPC activity patterns may positively predict subsequent remembering. Here, we separately measured mean (univariate) activity and pattern-based information in vPPC during memory encoding and separately assessed whether/how each measure related to subsequent remembering. Although stronger pattern-based information in temporal and frontal areas during encoding has been shown to predict subsequent remembering (Kuhl et al. 2012; Kim et al. 2014), prior studies have not, to our knowledge, specifically tested whether the strength of pattern-based information in vPPC predicts subsequent remembering and/or whether this effect would be present in precisely the same region or voxels that exhibit negative univariate subsequent memory effects.

We utilized data from two fMRI studies that have been previously described in relation to different questions (Kuhl et al. 2011, 2013). The two studies were independently conducted but highly similar in the task and stimuli used. In both studies, subjects learned (encoded) word–picture associations, with pictures that were drawn from two different visual categories (faces and scenes). Subjects were later tested, via cued recall, to remember the pictures associated with the word cues. Along with traditional univariate analysis, pattern classification analyses were applied to index the strength of visual category information reflected in distributed activity patterns. We focused our analyses

on ANG—an anatomically defined subregion of vPPC that has previously been shown to represent encoded/retrieved memories (Kuhl and Chun 2014) and also exhibits negative univariate subsequent memory effects (Uncapher and Wagner 2009). For comparison, we also considered two regions that typically show increased univariate activity during successful encoding (Kim 2011): ventral temporal cortex (VTC) and left inferior frontal gyrus (IFG). Consistent with prior findings, we expected subsequent remembering to be predicted by lower univariate encoding activity in ANG. More importantly, we hypothesized that reduced univariate encoding activity in vPPC and subsequent remembering would be associated with stronger pattern-based information in vPPC. We hypothesized that a dissociation between univariate and pattern-based predictors of subsequent remembering could be driven by reduced activity in “noninformative” voxels during memory encoding (Kok et al. 2012).

## Materials and Methods

Here, we provide a selective overview of relevant experimental procedures for each of the two studies (Fig. 1). More detailed descriptions of the participants, materials, full experimental design, and fMRI data acquisition can be found in Kuhl et al. (2011) for Study 1 and Kuhl et al. (2013) for Study 2. We also describe the fMRI analysis methods, which were consistent across Studies 1 and 2.

### Study 1 Methods

#### Participants

Eighteen subjects (10 female) between the ages of 18 and 27 participated in the study. All were right-handed native English speakers. Informed consent was obtained in accordance with procedures approved by the Stanford Institutional Review Board.

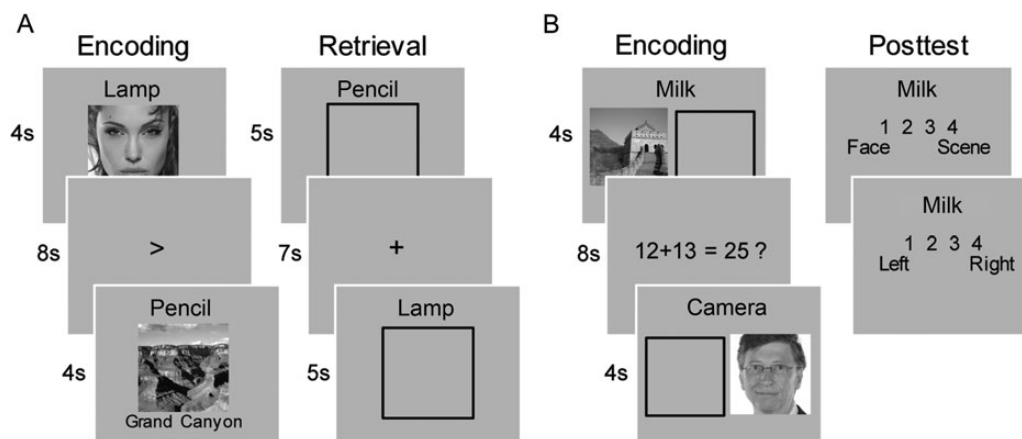
#### Materials

Stimuli used in the experiment were 96 nouns, 72 images of faces, and 72 images of scenes. All images were grayscale photographs of well-known people (e.g., Angelina Jolie) or locations (e.g., Grand Canyon). An additional 8 nouns, 4 faces, and 4 scenes were included as filler items.

#### Experimental Procedures

Across 7 alternating rounds of encoding and retrieval, subjects studied 144 word–image pairs (72 word–face pairs and 72 word–scene pairs). All encoding and retrieval rounds took place during fMRI scanning. During encoding blocks, subjects were instructed to study the association between the word and image so that they would later be able to retrieve the image when cued with the word. No overt responses were required during encoding trials. A name (e.g., Grand Canyon) was presented below each image. Each encoding trial lasted 4 s and was followed by an 8-s baseline period. During each inter-trial baseline period, subjects performed 6 trials of a simple visuospatial task, indicating the direction of an arrow by pressing a button. The baseline task was intended to prevent covert rehearsal.

During retrieval blocks, subjects were presented with cue words from the pairs they studied in the immediately preceding encoding block and covertly recalled the associated image. A blank square was presented below the cue word. Subjects indicated their retrieval success by making one of 5 responses using a 5-key button box: 1) “don’t know,” 2) “face-specific,” indicating that they remembered the specific image and that it was a face, 3) “face-general,” indicating that they had a nonspecific memory



**Figure 1.** Experimental paradigm. (A) Schematic of study and test trials in Study 1. Subjects studied word–face or word–scene pairs during encoding rounds and recalled the associate image of a cue word during retrieval rounds inside the scanner. (B) Schematic of study and test trials in Study 2. Subjects studied word–face or word–scene pairs during encoding rounds inside the scanner. During the baseline arithmetic task, numbers and signs were presented sequentially (not all at once) in the actual experiment. Subjects recalled both the category and the location of the associate image of a cue word during the posttest outside the scanner, but only category memory performance was used for subsequent memory analyses in the current study. Note: the schematic does not reflect the specific colors, fonts, and relative image sizes used in the actual experiment.

of a face, 4) “scene-specific,” and 5) “scene-general.” Each retrieval trial lasted 5 s and was followed by a 7-s fixation cross.

For reasons that are not the focus of the present study, some of the word–image pairs overlapped with other pairs. Specifically, over the course of the experiment, 24 of the 48 word cues were associated with 2 images (for details, see Kuhl et al. 2011). However, for these overlapping pairs, the first association was always encoded and tested before the second association was encoded/tested. To avoid potential interference-related effects, here we only consider the 24 pairs in the nonoverlapping condition along with the first associations for the 24 pairs in the overlapping condition. Subsequent memory analyses were based on retrieval accuracy during the retrieval blocks that immediately followed each encoding block.

#### fMRI Data Acquisition

Imaging data were collected on a 3T GE Signa MRI system at the Lucas Center at Stanford University. Functional images were obtained using a  $T_2^*$ -weighted 2D gradient echo spiral-in/out pulse sequence (TR = 2 s; TE = 30 ms; flip angle = 75°; 30 slices;  $3.4 \times 3.4 \times 4$  mm). The first 4 volumes from each scanning run were discarded to allow for  $T_1$  equilibration. Imaging data obtained during retrieval rounds were excluded from analysis.

## Study 2 Methods

### Participants

Twenty-six right-handed native English speakers (8 female) between the ages of 18 and 35 participated in the study. Two additional subjects were excluded due to excessive head motion. Informed consent was obtained in accordance with procedures approved by the Yale University Institutional Review Board.

### Materials

Stimuli consisted of nouns and pictures of faces and scenes, as in Study 1.

### Experimental Procedures

Subjects learned 72 noun–face and 72 noun–scene pairs across 12 alternating rounds of encoding and retrieval during fMRI

scanning. Each encoding block consisted of 12 trials. During an encoding trial, subjects were presented with a word and either a face or a scene image for 4 s. The word was horizontally centered on the screen, and the image appeared on the left or right side of the screen. Image location was varied across trials for reasons that are not relevant to the current analyses (Kuhl et al. 2013). The subjects’ task was to encode both the category (face or scene) and the location of the picture. Subjects completed an arithmetic task (addition of 2-digit numbers) during 8-s baseline periods following each encoding trial.

During retrieval blocks, subjects were tested on either the category or the location of images associated with cue words. Half (6) of all retrieval blocks tested category memory; half tested location memory. The two types of retrieval blocks were presented pseudo-randomly so that subjects could not anticipate the dimension to be retrieved and, therefore, could not selectively attend to the relevant dimension during encoding. Eight of the 12 pairs from each encoding block were tested in each retrieval block; therefore, one-third of the pairs remained untested. Each retrieval trial consisted of the presentation of a cue word along with a reminder of the test task and relevant response keys (i.e., “F–S–DK” for the category blocks, to indicate “face,” “scene,” or “don’t know” as response options; “L–R–DK” for the location blocks to indicate “left,” “right,” or “don’t know”). A retrieval trial lasted 4 s and was followed by an 8-s baseline period identical to the encoding blocks.

After exiting the scanner, subjects completed a surprise posttest that probed their memory for both the category and location of pictures paired with corresponding cue words. Every cue word studied in encoding rounds appeared in this phase. Subjects first indicated the category by making one of 4 responses: 1) definitely face, 2) probably face, 3) probably scene, or 4) definitely scene. Immediately after making their response, subjects indicated the picture location in the same way.

For our subsequent memory analyses, we focused only on category memory performance from the posttest. We did not consider memory performance from the retrieval blocks (which occurred inside the scanner), since only one-third of the encoded pairs were tested on category memory during the retrieval blocks. Although performance at posttest was influenced by the retrieval

blocks (Kuhl et al. 2013), this influence cannot explain potential relationships between encoding activity and posttest performance (since encoding trials obviously preceded corresponding retrieval trials). Therefore, although the retrieval phase likely introduced “noise” to the subsequent memory analyses, it does not represent a potential confound. Moreover, since the subsequent memory analyses in Study 1 were based on performance on an immediate retrieval test, if findings are consistent across Studies 1 and 2, this would attest to the generalizability and robustness of the findings.

#### fMRI Data Acquisition

Imaging data were collected on a 3T Siemens Trio scanner at the Anlyan Center at Yale University. Functional data were obtained using a  $T_2^*$ -weighted gradient EPI sequence (TR = 2 s; TE = 25 ms; flip angle = 90°; 34 slices;  $3.5 \times 3.5 \times 4$  mm). The first 5 volumes from each scanning run were discarded. Volumes from both encoding and retrieval rounds were included in analysis.

#### fMRI Data Analysis

##### Preprocessing

fMRI data preprocessing was conducted using SPM8 (Wellcome Department of Cognitive Neurology, London). Images were first corrected for slice acquisition timing and head motion. High-resolution anatomical images were co-registered to functional images and segmented into gray matter, white matter, and cerebrospinal fluid. Segmented gray matter images were skull-stripped and normalized to the Montreal Neurological Institute (MNI) template. Functional images were normalized using the parameters generated during normalization of the anatomical image. Functional images were resampled to 3-mm cubic voxels and smoothed with an 8 mm FWHM Gaussian kernel.

##### Univariate Amplitude Analysis

Univariate data analyses were conducted under the assumptions of the general linear model (GLM) using SPM8. To perform analyses that link trial-wise univariate amplitude and multi-voxel classification results, we estimated univariate activation for single trials. This was achieved by modeling each trial as a separate regressor, convolved with a canonical haemodynamic response function. Scanning blocks and six motion parameters were included as regressors of no interest. One-sample *t*-tests against a contrast value of 0 were performed on the resulting parameter estimates to obtain *t*-values (parameter estimates normalized by unexplained variance) for each voxel. To obtain a measure of univariate response amplitude for a given region of interest (ROI), for each trial we computed the mean *t*-value across all voxels within that ROI.

Additionally, from the same model, encoding trials were contrasted according to visual category (Face vs. Scene) and subsequent memory (Remembered vs. Forgotten) to generate subject-specific statistical parametric maps. The resulting contrast maps were entered into a group-level one-sample *t*-test against 0 in which subjects were treated as a random factor.

##### Multi-Voxel Pattern Classification Analysis

Pattern classification analyses were performed with the Princeton MVPA toolbox [<https://code.google.com/p/princeton-mvpa-toolbox>] (Last accessed 7 April 2016) and custom Matlab (Mathworks, Natick, MA, USA) scripts. The trial-by-trial *t*-values generated from the univariate analysis were extracted for every voxel within an ROI, yielding patterns of voxel activations for each trial. No feature selection or further transformation of

data was performed. Thus, the only difference between multi-voxel patterns and univariate amplitude was that *t*-values were not averaged across voxels for multi-voxel classification. It should be noted that while multi-voxel patterns were generated from smoothed data, we observed qualitatively identical results using unsmoothed data (see [Supplementary Fig. 1](#)). For each ROI, a penalized (L2) logistic regression classifier was trained to discriminate Face versus Scene trials from encoding rounds. The classifier was trained and tested with a leave-one-trial-out cross-validation procedure. A test trial was considered successfully classified if the classifier “guessed” the category to which the image belonged. Classification accuracy was used to assess the overall performance of the classifier. For the subsequent memory and correlation analyses, we used the continuous output of the classifier (hereinafter, “classifier evidence”), which ranged between 0 and 1 and signified the relative probability of face versus scene evidence (Kuhl et al. 2012). Because face and scene evidence were opposite ends of the output continuum, face evidence was equivalent to 1–scene evidence and vice versa. For all of the face trials, we used classifier evidence for the face category and for all of the scene trials, we used classifier evidence for the scene category.

##### ROI Definition

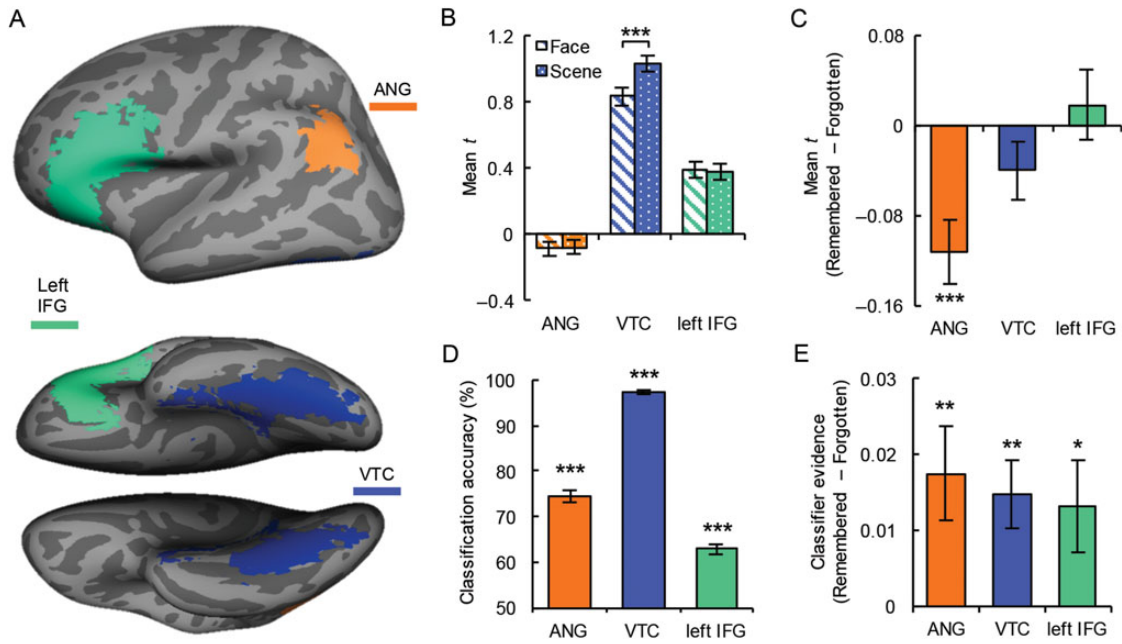
We anatomically defined three a priori ROIs as shown in [Figure 2A](#): angular gyrus (ANG), ventral temporal cortex (VTC), and the left inferior frontal gyrus (IFG). All anatomical masks were created from the Anatomical Automatic Labeling (AAL) atlas (Tzourio-Mazoyer et al. 2002) and were in standardized (MNI) space. VTC was defined as a combination of the regions corresponding to the AAL atlas for parahippocampal gyrus (PHG) and fusiform gyrus (FG). For additional analyses, we also created a larger vPPC mask by combining regions labeled as ANG, temporoparietal junction (TPJ), and supramarginal gyrus (SMG) in Kuhl et al. (2013). All ROIs were further masked by individual subjects’ whole-brain mask (generated during GLM analysis) to exclude voxels without univariate statistics. Thus, the number of voxels included in the anatomical as well as functional ROIs varied across subjects (636–884 in ANG; 1501–2396 in VTC; 1381–1528 in left IFG; 2706–3098 in vPPC).

To improve the specificity of localization, we additionally defined finer-grained subregions of vPPC based on cortical parcellations estimated by resting-state functional connectivity (Yeo et al. 2011) ([Fig. 3A](#)). Specifically, we used the liberal mask of the 17-network parcellation available in FreeSurfer [<http://surfer.nmr.mgh.harvard.edu>] (Last accessed 7 April 2016). For each of the seven networks that at least partially included vPPC (Networks 7, 8, 12, 13, 15, 16, and 17), we extracted separate left and right subregions, producing a total of 14 subregion ROIs. All subregion ROIs were co-registered to the same standardized (MNI) space as functional images and masked by subject-specific whole-brain masks. ROIs were visualized on the inflated surface of an averaged template brain supplied by FreeSurfer.

## Results

### Behavioral Results

Subjects were able to correctly recall the category of the image for the majority of studied pairs in both Study 1 and Study 2. In Study 1, items with either “specific” or “general” memory accuracy were counted as “Remembered” ( $M = 79.2\%$ ), and items with “don’t know” or incorrect responses (“specific” or “general” memory for the opposite category) were considered “Forgotten” ( $M = 13.2\%$  and  $5.7\%$ , respectively). Trials for which no response was made



**Figure 2.** Univariate amplitude and pattern-based information in anatomical ROIs. (A) Anatomical ROIs defined from the AAL atlas (orange = ANG, blue = VTC, green = left IFG), visualized on the inflated surface of a template brain (top = left lateral view, bottom = ventral view). (B) Mean  $t$ -statistics across voxels for Face and Scene trials. (C) Univariate subsequent memory effects (difference between the mean  $t$ -statistics of Remembered vs. Forgotten trials) for each ROI. Significance reflects difference from zero. (D) Overall Face versus Scene decoding accuracy in each ROI. Significance reflects comparison to chance (50%). (E) Pattern-based subsequent memory effects (difference between the classifier evidence for Remembered vs. Forgotten trials) in each ROI. Significance reflects difference from zero. In B–E, means and standard errors of the means (SEM) were computed from the data collapsed across studies for illustrative purposes. Significance was determined from statistical tests including study as a factor. Error bars = SEM across subjects, \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$  (not corrected for multiple comparisons).

during retrieval ( $M = 2.0\%$ ) were excluded from the subsequent memory analysis. In Study 2, “Remembered” items corresponded to items with high-confidence correct category memory during posttest ( $M = 54.4\%$ ). “Forgotten” trials included both low-confidence correct trials and incorrect trials ( $M = 21.0\%$  and  $24.6\%$ , respectively). The definitions of Remembered versus Forgotten bins for Studies 1 and 2 were consistent with the definitions used in previous reports of these data (Kuhl et al. 2012, 2013). That said, it should be noted that it is impossible to perfectly align the two studies given differences in the test format—for example, Study 1 included a “Don’t Know” option, whereas Study 2 did not, and Study 1 asked subjects to try to recall the specific item, whereas Study 2 only asked subjects to recall the visual category. Importantly, however, changing the binning criteria did not alter the core results (see [Supplementary Fig. 2](#)).

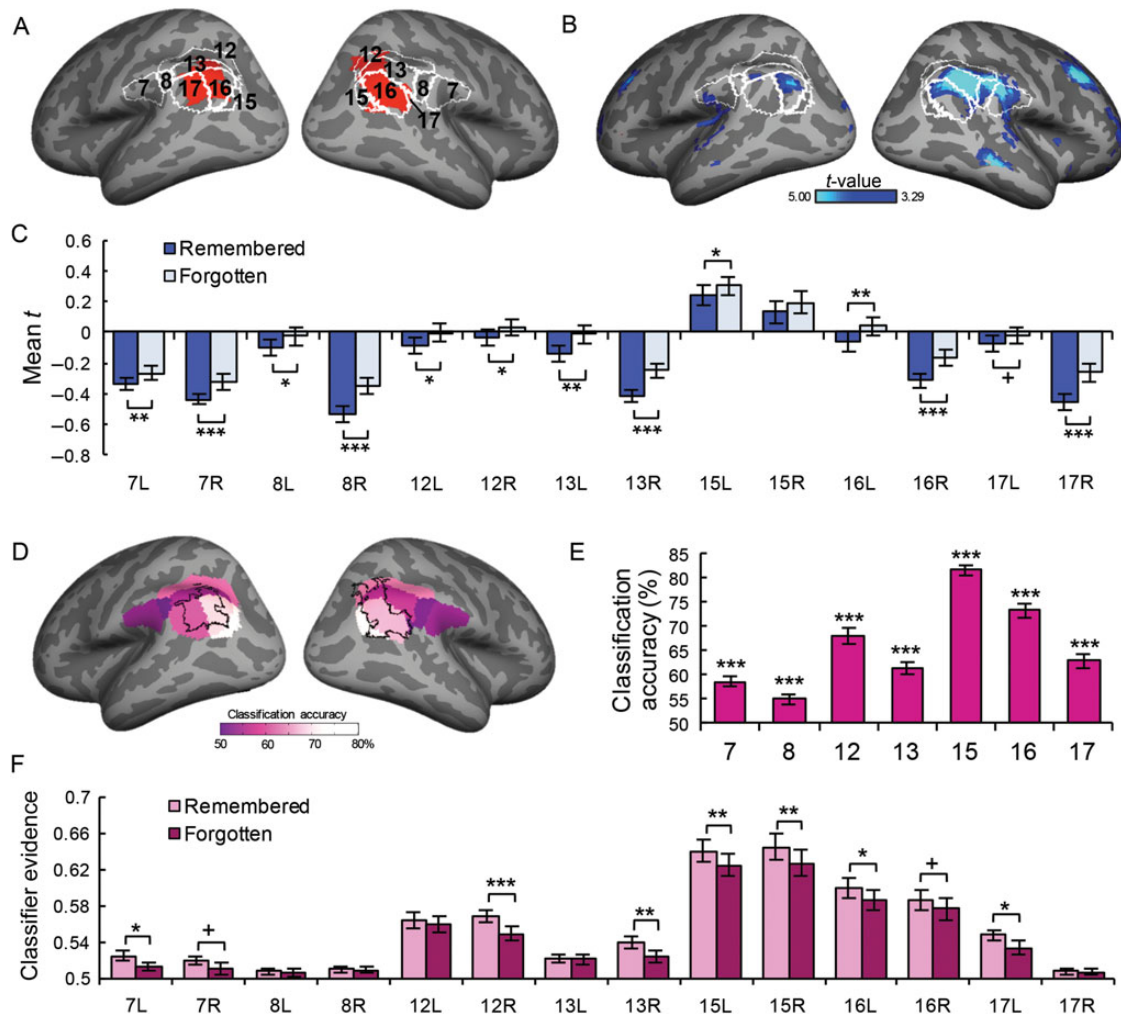
Memory accuracy (the percentage of Remembered items) did not differ for faces versus scenes in Study 1 ( $M = 80.1\%$  vs.  $78.2\%$ , respectively,  $t_{(17)} = 1.14$ ,  $P = 0.27$ ), but accuracy was higher for faces than scenes in Study 2 ( $M = 59.8\%$  vs.  $49.0\%$ , respectively,  $t_{(25)} = 5.05$ ,  $P < 0.001$ ). Detailed behavioural results can be found in previously published reports (Kuhl et al. 2011, 2013).

### Univariate Subsequent Memory Effects

We first examined the overall magnitude of BOLD responses in each ROI during encoding trials, regardless of memory success. Because Studies 1 and 2 were analyzed with the same procedures, we combined the data from the two studies. As shown in [Figure 2B](#), response amplitudes in ANG were lower than in VTC or left IFG, with mean  $t$ -values tending to be negative, relative to the baseline. For each ROI, we also performed 2 (face, scene)  $\times$  2 (Study 1, Study 2) repeated-measures ANOVAs. In ANG and left

IFG, BOLD responses were slightly higher for scenes than faces in Study 1, while the opposite was true in Study 2. This interaction was marginally significant in ANG ( $F_{1,42} = 3.89$ ,  $P = 0.055$ ) and IFG ( $F_{1,42} = 2.89$ ,  $P = 0.097$ ), without main effects of image category ( $F_s < 1$ ). In VTC, however, response amplitudes were higher for scenes than faces ( $F_{1,42} = 53.38$ ,  $P < 0.001$ ) without an interaction ( $F < 1$ ). All three ROIs showed generally lower activation in Study 1 than in Study 2 ( $P_s < 0.05$ ), possibly due to differences in the inter-trial baseline task.

Of central importance, we also compared mean  $t$ -values for Remembered versus Forgotten trials (collapsed across image categories) for each ROI to test for subsequent memory effects. A 2 (Remembered, Forgotten)  $\times$  2 (Study 1, Study 2) repeated-measures ANOVA revealed that univariate encoding activation in ANG was lower for subsequently Remembered than subsequently Forgotten images ( $F_{1,42} = 14.83$ ,  $P < 0.001$ ; significant following Bonferroni correction; [Fig. 2C](#)), consistent with previous findings (Uncapher and Wagner 2009). The negative subsequent memory effect did not interact with study number ( $F < 1$ ). Follow-up tests confirmed that the negative subsequent memory effect was present in both Study 1 ( $t_{(17)} = 2.19$ ,  $P = 0.043$ ) and Study 2 ( $t_{(25)} = 3.46$ ,  $P = 0.002$ ). Additional analyses indicated that this negative univariate subsequent memory effect was consistent across almost all vPPC subregions (significant or marginally significant in 13 of the 14 subregions), both within and outside ANG ([Fig. 3B,C](#); see [Supplementary Fig. 3](#) for whole-brain results). In left IFG, the main effect of subsequent memory was not significant ( $F < 1$ ), but there was a significant interaction between subsequent memory and study number ( $F_{1,42} = 5.58$ ,  $P = 0.023$ ). This interaction reflected a nonsignificant effect of memory success in Study 1 ( $t_{(17)} = 1.06$ ,  $P = 0.305$ ) and a significant positive subsequent memory effect in Study 2 ( $t_{(25)} = 2.95$ ,  $P = 0.007$ ). In VTC,



**Figure 3.** Univariate and pattern-based subsequent memory effects in subregions of vPPC. (A) vPPC subregions based on cortical parcellation estimated by intrinsic functional connectivity (Yeo et al. 2011), visualized on the lateral surface of both hemispheres of the FreeSurfer template brain. White lines demarcate the boundaries of each subregion. Black numbers denote the names of the networks from which each subregion is derived. Red areas indicate ANG defined from the AAL atlas. (B) Group-level whole-brain map of brain regions exhibiting negative univariate subsequent memory effects, thresholded at  $P < 0.001$  ( $t = 3.29$ , uncorrected). White lines demarcate the boundaries of each vPPC subregion. See [Supplementary Figure 3](#) for medial views and analysis details. (C) Mean univariate amplitudes (t-value) for Remembered and Forgotten trials in each vPPC subregion. Significance was determined from ANOVAs including study as a factor. (D) Face versus Scene classification accuracy map of vPPC subregions. Accuracies were averaged over all subjects, collapsed across studies. Lighter colors indicate higher classification accuracy. Black lines indicate ANG defined from the AAL atlas. (E) Classification accuracies in bilateral vPPC subregions. Significance reflects difference from chance (50%). (F) Classifier evidence for Remembered and Forgotten trials in vPPC subregions. Significance was determined from ANOVAs including study as a factor. In C, E, F, means and SEMs were computed from the data collapsed across studies for illustrative purposes. Error bars = SEM across subjects, \* $P < 0.1$ , \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$  (not corrected for multiple comparisons).

neither the main effect of memory success ( $F_{1,42} = 2.31$ ,  $P = 0.136$ ) nor the interaction between subsequent memory and study number ( $F < 1$ ) was significant.

To assess whether univariate subsequent memory effects varied across the face and scene categories, we performed additional ANOVAs including image category as an independent variable (along with subsequent memory and study number). The subsequent memory effect did not interact with category in any of the ROIs ( $P_s > 0.165$ ).

### Multi-Voxel Pattern-Based Subsequent Memory Effects

To first assess the overall performance of the pattern classifiers for each ROI, we compared the percentage of correctly classified trials (collapsed across all conditions) against chance

performance (50%). [Note: pattern classification results from IFG and VTC in Study 1 have previously been reported (Kuhl et al. 2012), although the specific analysis details and ROI definitions were slightly different in the current study]. Mean classification accuracies were well above chance in each of the ROIs in both Study 1 (ANG: 74%, VTC: 97%, left IFG: 61%;  $t_{(17)}s > 6.74$ ,  $P_s < 0.001$ ) and Study 2 (ANG: 75%, VTC: 98%, left IFG: 65%;  $t_{(25)}s > 9.45$ ,  $P_s < 0.001$ ), all significant after correcting for multiple comparisons. Figure 2D illustrates mean classification accuracies for each ROI, collapsing across studies. Overall classification accuracy was significantly or marginally above chance in all finer-grained vPPC subregions as well, with the most posterior region at the occipito-parietal junction showing the highest performance (Fig. 3D,E).

The above-chance decoding accuracy in ANG indicates that ANG voxel activity patterns contained robust information about

the visual categories of encoded stimuli, despite the fact that there was no positive univariate response during encoding trials in ANG. We next addressed whether the category information reflected within ANG activity patterns was related to subsequent remembering. This analysis was nearly identical to the subsequent memory analyses described above, with the difference being that here we used classifier-derived category evidence—as opposed to univariate activation—as a “predictor” of later memory. For each ROI, we ran a 2 (Remembered, Forgotten)  $\times$  2 (Study 1, Study 2) ANOVA. As previously reported (Kuhl et al. 2012), positive subsequent memory effects were observed in VTC and left IFG ( $F_{1,42S} > 4.97$ ,  $P_s < 0.05$ ). Critically, a positive relationship between classifier evidence and subsequent remembering was also observed in ANG ( $F_{1,42} = 8.27$ ,  $P = 0.006$ ), despite the fact that univariate activation in ANG was negatively related to subsequent remembering (Fig. 2E). The main effect of this positive pattern-based subsequent memory effect in ANG remained significant when correcting for multiple comparisons. Follow-up comparisons indicated that positive pattern-based subsequent memory effects in ANG were marginally significant in both Study 1 ( $t_{(17)} = 1.97$ ,  $P = 0.066$ ) and Study 2 ( $t_{(25)} = 1.98$ ,  $P = 0.059$ ). Additional analyses revealed that the positive pattern-based subsequent memory effect was distributed across vPPC subregions, being significant or marginally significant in 9 of the 14 subregions (Fig. 3F). There was no main effect of study on overall classifier evidence in ANG ( $F < 1$ ), but classifier evidence was marginally greater in Study 2 than Study 1 in left IFG ( $F_{1,42} = 3.21$ ,  $P = 0.08$ ) and significantly greater in Study 2 than Study 1 in VTC ( $F_{1,42} = 12.03$ ,  $P = 0.001$ ). Study number did not interact with the positive pattern-based subsequent memory effects in any of the ROIs ( $P_s > 0.442$ ). We also tested whether image category was confounded with subsequent memory by adding the category variable as a factor, but did not observe either category  $\times$  subsequent memory or category  $\times$  subsequent memory  $\times$  study number interactions in ANG or left IFG ( $P_s > 0.25$ ). In VTC, subsequent memory effects were marginally more positive for faces than scenes ( $F_{1,42} = 3.18$ ,  $P = 0.082$ ) without a category  $\times$  subsequent memory  $\times$  study number interaction ( $F < 1$ ).

To test whether the positive pattern-based subsequent memory effect was observed simply because more Remembered than Forgotten trials were used to train the classifier, we ran a control analysis where we artificially balanced the number of trials. For each subject, we randomly selected the same number of training trials from each of the category and subsequent memory conditions (i.e., Face-Remembered, Face-Forgotten, Scene-Remembered, Scene-Forgotten) in each cross-validation iteration. We used the maximum number of trials available and removed a small subset of subjects (4 subjects from Study 1 and 1 subject from Study 2) who ended up with  $< 5$  trials per condition. We repeated the analysis 100 times per subject, with a different random selection of trials for each iteration, and averaged the results over iterations to produce a single result for each subject. Despite the reduction in power, the results remained qualitatively identical: the positive pattern-based subsequent memory effect in ANG was statistically significant ( $F_{1,37} = 5.16$ ,  $P = 0.029$ ), and this effect was not significantly different from the effect we found in the unbalanced data ( $F < 1$ ).

We further tested whether pattern-based information in ANG had independent predictive power with respect to subsequent memory by conducting a separate analysis that controlled for univariate amplitude in ANG. For each study, we ran a mixed-effect logistic regression in which each trial served as a data point. As fixed effects, we included classifier evidence, univariate amplitude, and the interaction between the two, as well as stimulus

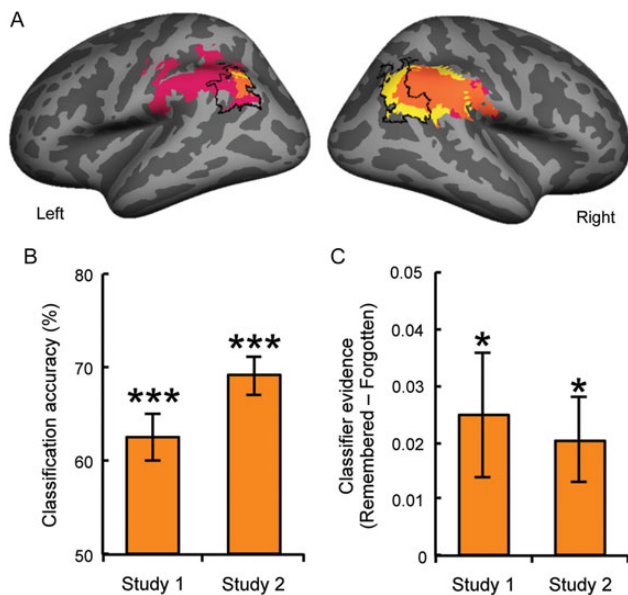
category. The classifier evidence and univariate amplitude were z-scored across all data points prior to the analysis. The model for Study 2 additionally included the stimulus location and the subjects' task during each retrieval block as fixed effects. An intercept for subjects and by-subject random slopes for all fixed effects were included as random effects. We performed likelihood ratio tests for the full models against the null models including all independent variables except for the classifier evidence and found that the full model yielded significantly better fits in both Study 1 ( $\chi^2(1) = 4.38$ ,  $P = 0.036$ ) and Study 2 ( $\chi^2(1) = 5.02$ ,  $P = 0.02$ ). In other words, in both studies classifier evidence predicted subsequent memory outcomes beyond what was accounted for by univariate amplitude alone. The interaction between univariate amplitude and classifier evidence was not significant in either study ( $P_s > 0.11$ ).

### Pattern-Based Analyses in Functional ROIs

The preceding analyses indicate that ANG exhibited a negative univariate subsequent memory effect as well as a positive pattern-based subsequent memory effect. For these analyses, we focused on an anatomically defined angular gyrus ROI. However, it is possible that distinct clusters of voxels within the ANG ROI contributed to each of these effects. Additionally, negative univariate subsequent memory effects have been shown to extend from angular gyrus into supramarginal gyrus (Uncapher and Wagner 2009; Kim 2011), which raises the concern that our anatomical ANG ROI may not have fully captured voxels exhibiting negative univariate subsequent memory effects. We therefore tested whether the positive pattern-based subsequent memory effects were present in group-level, functionally defined ROIs. Specifically, we identified voxels that exhibited the largest negative subsequent memory effects in vPPC, separately for Studies 1 and 2 (Fig. 4A). The group-level subsequent memory contrasts yielded vPPC clusters that spanned ANG and SMG in Study 1 (right hemisphere peak:  $x = 60$ ,  $y = -28$ ,  $z = 31$ ; left hemisphere peak:  $x = -66$ ,  $y = -22$ ,  $z = 28$  mm in MNI space) and Study 2 (right hemisphere peak:  $x = 60$ ,  $y = -40$ ,  $z = 46$ ; left hemisphere peak:  $x = -39$ ,  $y = -70$ ,  $z = 37$  mm).

To build the ROIs, we applied a liberal threshold of  $P < 0.05$  (uncorrected) to the group-level statistical maps within vPPC and selected clusters containing the peak voxel for each hemisphere. This resulted in separate bilateral ROIs for each study, which largely overlapped each other as well as the anatomical ANG ROI. The numbers of total voxels (left + right) were 1482 for Study 1 and 1114 for Study 2 (see Supplementary Table 1 for further details of the functional ROIs). Overall decoding accuracies in the functional ROIs were well above chance in both Study 1 ( $M = 63\%$ ,  $t_{(17)} = 4.91$ ,  $P < 0.001$ ) and Study 2 ( $M = 69\%$ ,  $t_{(25)} = 9.20$ ,  $P < 0.001$ ), indicating robust sensitivity to category information (Fig. 4B). To test whether classifier evidence within these functional ROIs predicted subsequent memory, we applied an ANOVA with factors of subsequent memory and study number. The main effect of subsequent memory was significant ( $F_{1,42} = 12.39$ ,  $P = 0.001$ ) with no interaction with the study number ( $F < 1$ ). As shown in Figure 4C, post hoc t-tests revealed significant positive pattern-based subsequent memory effects in both Study 1 ( $t_{(17)} = 2.23$ ,  $P = 0.039$ ) and Study 2 ( $t_{(25)} = 2.74$ ,  $P = 0.011$ ).

Finally, as an even more stringent test of the overlap between the negative univariate subsequent memory effects and the positive pattern-based subsequent memory effects, we also generated subject-specific ROIs that consisted only of the vPPC voxels for each subject that displayed numerically negative univariate subsequent memory effects ( $t < 0$ , from the Remembered vs.



**Figure 4.** Multi-voxel classification results in functional ROIs. (A) Group-level functional vPPC ROIs that exhibit negative univariate subsequent memory effects, defined separately for Study 1 (magenta) and Study 2 (yellow). Orange areas denote the overlap between the two studies. Black outlines indicate the anatomically defined ANG ROI. (B) Overall Face versus Scene decoding accuracies in the functional ROIs from each study. Significance reflects comparison to chance (50%). (C) Pattern-based subsequent memory effects (difference between the classifier evidence for Remembered vs. Forgotten trials) in the functional ROIs from each study. Significance reflects difference from 0. Error bars = SEM across subjects, \* $P < 0.05$ , \*\*\* $P < 0.001$  (not corrected for multiple comparisons).

Forgotten contrast). Again, we found that classifier-derived evidence positively predicted subsequent remembering ( $F_{1,42} = 13.33$ ,  $P < 0.001$ ). Thus, within the specific vPPC clusters (and voxels) that exhibited negative univariate subsequent memory effects, activity patterns robustly reflected the category of encoded stimuli, and the strength of this pattern-based information positively predicted subsequent remembering. Data from functionally defined ROIs in other cortical areas are reported in [Supplementary Figure 4](#).

### Relationship Between Univariate Amplitude and Classifier Evidence

The dissociation between negative univariate versus positive pattern-based subsequent memory effects in ANG suggests that reduced univariate activation is associated with increased pattern-based information. To directly test this, we computed within-subject, trial-level correlations between mean univariate activation and classifier evidence, separately for each ROI (collapsed across conditions). Individual subjects' Spearman correlation coefficients ( $\rho$ ) were transformed to Fisher's z-scores and compared against 0 using one-sample t-tests. We found negative correlations between univariate activation and pattern-based information in ANG in both Study 1 ( $t_{(17)} = 2.57$ ,  $P = 0.02$ ) and Study 2 ( $t_{(25)} = 3.01$ ,  $P = 0.006$ ) (Fig. 5A,B). In contrast, positive correlations between mean univariate activation and classifier evidence were observed in VTC (Study 1:  $t_{(17)} = 2.85$ ,  $P = 0.011$ ; Study 2:  $t_{(25)} = 2.30$ ,  $P = 0.03$ ; Fig. 5A,B). Correlations were not significantly different from 0 in left IFG ( $P > 0.58$ ). The strength of correlations did not differ across the studies for any of the ROIs ( $P > 0.4$ ). Importantly, negative correlations were observed in ANG even when only considering subsequently remembered trials (Study

1:  $t_{(17)} = 2.99$ ,  $P = 0.008$ ; Study 2:  $t_{(25)} = 2.42$ ,  $P = 0.023$ ), indicating that the negative correlation indeed reflects trial-by-trial variations and was not a mere consequence of the overall difference between Remembered and Forgotten trials.

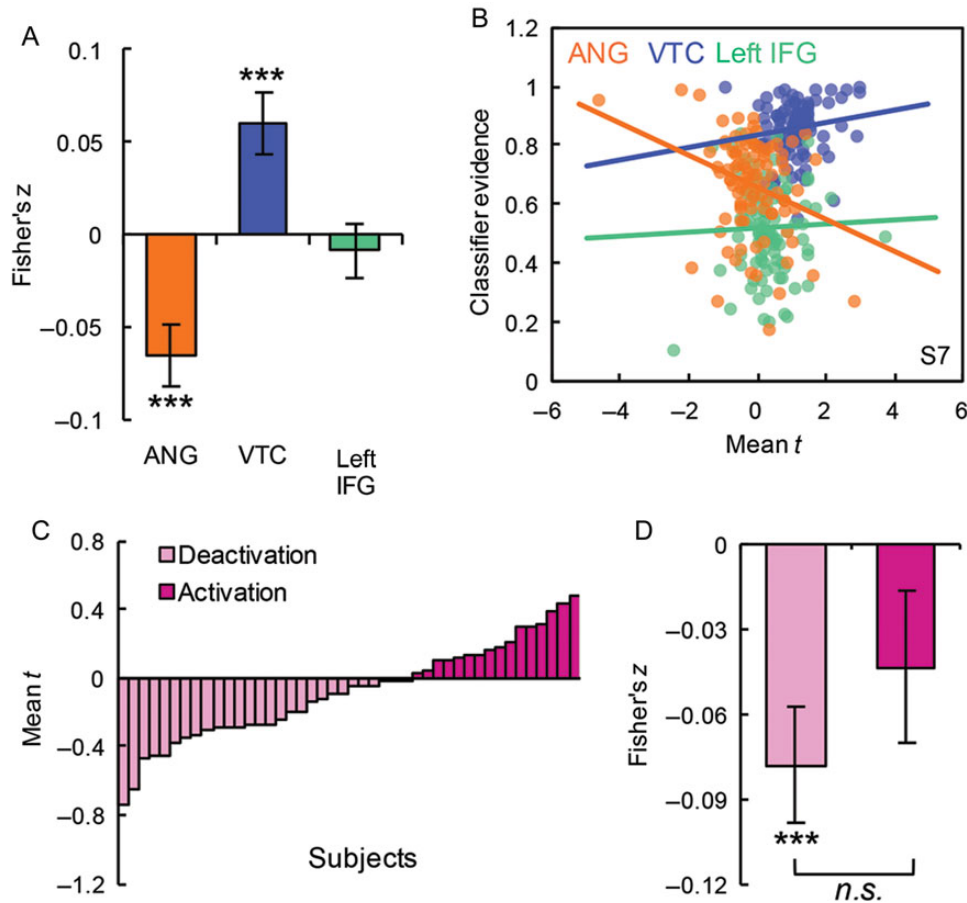
Given that the univariate response amplitude in ANG tended to be negative, one possibility is that the negative correlation in ANG can be explained in terms of signal-to-noise ratio. That is, trials with lower univariate response amplitude would naturally have higher signal-to-noise ratio (i.e., greater deflection from baseline), which should relate to better classifier performance (Smith et al. 2011; Tong et al. 2012). To test this idea, we divided all 44 subjects from both studies into two groups (Fig. 5C), depending on whether their mean t statistic in ANG across all conditions and trials was below 0 (deactivation group,  $N = 28$ ; 16 from Study 1) or above 0 (activation group,  $N = 16$ ; 2 from Study 1). If the negative correlation in ANG was purely a consequence of overall deactivation, the activation group should show positive rather than negative correlations between univariate activation and classifier evidence. However, the trial-level correlation did not significantly differ between the groups ( $P = 0.311$ ; Fig. 5D), with a significant negative relationship for the deactivation group ( $M = -0.078$ ,  $t_{(27)} = 3.82$ ,  $P < 0.001$ ) and a qualitatively similar trend for the activation group ( $M = -0.043$ ,  $t_{(15)} = 1.60$ ,  $P = 0.13$ ). The sample size was also smaller for the activation group. Thus, the negative correlation between mean univariate activation and pattern-based information in ANG cannot be explained by below-baseline activation during encoding trials.

### Univariate Subsequent Memory Effects as a Function of Voxel Selectivity

How does lower activation in ANG translate to stronger information? One possible explanation is that neural responses become "sharper": that reduced activation preferentially occurs within voxels that are not sensitive to the category of the to-be-encoded stimulus (Kok et al. 2012). To test this idea, we compared univariate subsequent memory effects within voxels across different levels of category sensitivity. Using the t-statistics of the subject-specific univariate Face versus Scene contrast, we split all voxels in ANG into two sets: face-preferring voxels (positive t-values) and scene-preferring voxels (negative t-values). Each of these sets were further divided into 10 equal-sized bins, which produced 20 subject-specific sets of voxels rank-ordered by category preference. For each of the 20 voxel bins, we computed the univariate subsequent memory effect separately for face and scene trials by taking the difference between the mean amplitudes of Remembered and Forgotten trials. Data were then aggregated across the two studies.

As shown in Figure 6A, for face and scene trials, negative subsequent memory effects were small or absent in the voxels that were most sensitive to the category of the to-be-encoded stimulus. Instead, negative subsequent memory effects were relatively more apparent in the voxels that were not tuned for the to-be-encoded stimulus (either voxels with no strong category preference or voxels with a preference for the "other category"). As depicted in Figure 6B, there was a significant negative linear trend across the bins "preferring" the to-be-encoded stimulus category (i.e., an average of face-preferring voxels for face trials and scene-preferring voxels for scene trials) ( $F_{1,42} = 10.94$ ,  $P = 0.002$ ). In other words, across the voxels that had a numerical preference for the to-be-encoded stimulus, the negative subsequent memory effect increased as category preference decreased. Across the voxels that did not prefer the to-be-encoded stimulus ("non-preferring" voxels), the linear trend relating category preference





**Figure 5.** Relationship between univariate activation and classifier evidence. (A) Within-subject, cross-trial Spearman correlations (Fisher's z-transformed) between univariate amplitude and classifier evidence. Means and SEMs were computed from the data collapsed across studies. Significance reflects difference from 0. (B) Cross-trial correlation between univariate amplitude and classifier evidence for each ROI (orange = ANG, blue = VTC, green = left IFG) from a representative subject in Study 1. Each point in the plot represents a single encoding trial. (C) Overall univariate amplitude in ANG rank-ordered by subject. All subjects from Study 1 and Study 2 were collapsed together and divided into two groups depending on whether their mean t-statistic across all trials was below 0 (Deactivation,  $N = 28$ ) or above 0 (Activation,  $N = 16$ ). (D) Within-subject, cross-trial Spearman correlation (Fisher's z-transformed) between univariate amplitude and classifier evidence in ANG, averaged separately for the groups with overall ANG deactivation (pink) or activation (magenta). Error bars = SEM across subjects, \*\*\* $P < 0.001$  (not corrected for multiple comparisons).

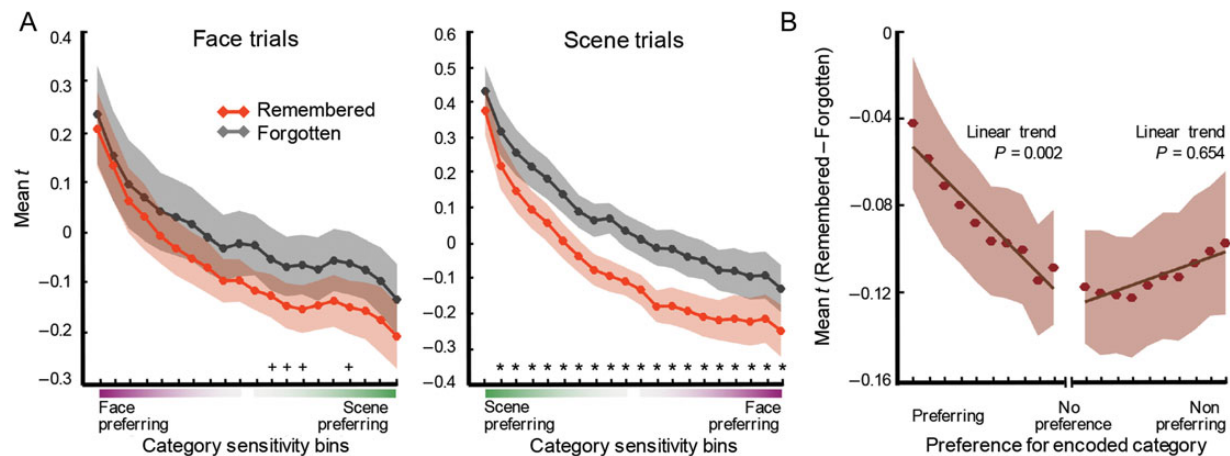
and subsequent memory magnitude was not significant ( $F < 1$ ). Together, these results indicate that negative subsequent memory effects were relatively most apparent in voxels with low preference for the to-be-encoded stimulus, helping to explain why/how there was a negative relationship between mean univariate activation and classifier evidence.

## Discussion

The subsequent memory paradigm has been extensively used to identify brain regions that positively contribute to successful encoding (for reviews, see Paller and Wagner 2002; Kim 2011). Subsequent memory analyses have consistently revealed positive subsequent memory effects in medial temporal lobe and inferior prefrontal regions (Fernández and Tendolkar 2001; Kim 2011) as well as negative subsequent memory effects in regions including vPPC (Otten and Rugg 2001; Wagner and Davachi 2001; Daselaar et al. 2004). That is, lower vPPC activation tends to predict better remembering. This has led to the proposal that vPPC activation reflects task-irrelevant processing, such as shifting of attention away from encoded material (Cabeza et al. 2012) or internally oriented mental processing unrelated to the to-be-encoded event

(Kim et al. 2010). Here, we directly compared encoding-related univariate vPPC activity and pattern-based information within vPPC as predictors of subsequent remembering.

Consistent with prior studies, we found that mean univariate activation in vPPC during encoding was negatively related to subsequent remembering: lower activation strongly predicted better remembering. However, multi-voxel pattern classification analysis revealed that the same vPPC region that exhibited negative univariate subsequent memory effects contained information about the visual categories of encoded items, as reflected in highly robust classification accuracy. Moreover, in contrast to univariate activation, pattern-based information in vPPC positively predicted subsequent memory: stronger classifier evidence predicted better subsequent remembering. Additionally, across individual learning trials, we observed a negative correlation between mean univariate amplitude and pattern-based information. This dissociation was at least partly explained by the fact that univariate activation reductions that predicted subsequent memory were most evident in voxels with low preference for the to-be-encoded stimulus. Collectively, these findings indicate that vPPC activity patterns reflect the content and quality of encoding.



**Figure 6.** Univariate subsequent memory effects as a function of voxel category selectivity. (A) Subject-specific Face versus Scene contrasts were used to generate sets of face-preferring voxels (positive  $t$ -values) and scene-preferring voxels (negative  $t$ -values). Each set was then divided into 10 bins of equal size, ranked by strength of category preference. For Face encoding trials (left panel), the leftmost bin reflects the most face-preferring voxels and the rightmost bin reflects the most scene-preferring voxels. For Scene encoding trials, this ordering was reversed (left = scene-preferring, right = face-preferring). Bins toward the middle reflect voxels with no category preference. Symbols above the  $x$ -axes indicate the significance of the main effect of subsequent memory for each category sensitivity bin, determined from 2 (Remembered, Forgotten)  $\times$  2 (Study 1, Study 2) ANOVAs. \* $P < 0.1$ , \*\* $P < 0.05$  (not corrected for multiple comparisons). (B) Subsequent memory effects as a function of voxel preference for the category of the to-be-encoded stimulus (averaged across Face and Scene trials). Among voxels with a preference for the category of the to-be-encoded stimulus (“preferring” voxels; leftmost bins), there was a negative relationship between the magnitude of the negative subsequent memory effect and the strength of voxel preference ( $F_{1,42} = 10.94$ ,  $P = 0.002$ ). Among voxels that did not prefer the category of the to-be-encoded stimulus (“nonpreferring” voxels; rightmost bins), there was no linear relationship between the magnitude of the negative subsequent memory effect and the strength of voxel preference ( $F < 1$ ). Solid lines indicate best fitting lines. For both A and B, means and SEMs were computed from data collapsed across studies for illustrative purposes. Shaded areas indicate SEM across subjects.

### vPPC Activity Patterns Reflect Encoded Information

Despite a growing interest in the nature of parietal contributions to memory (Cabeza et al. 2008; Hutchinson et al. 2009; Uncapher and Wagner 2009; Berryhill 2012; Gilmore et al. 2015), relatively few studies have applied pattern-based analyses to probe the information reflected in parietal activity patterns. In particular, because of the consistent finding of negative univariate subsequent memory effects in vPPC—and the corresponding conclusion that vPPC does not contribute to successful encoding—there has been virtually no direct consideration of the information contained within vPPC activity patterns during encoding. However, findings from a pair of recent studies provide some initial evidence that vPPC activity patterns reflect encoded content.

In one study, Xue et al. (2012) compared neural activity patterns across repeated presentations of visual stimuli and then tested whether the consistency of neural activity patterns predicted subsequent remembering. Within vPPC (and angular gyrus, more specifically), the consistency of activity patterns across presentations of the same stimulus was predictive of subsequent remembering. Importantly, this result was selective to similarity between presentations of the same stimulus—and not across presentations of different stimuli—suggesting that vPPC reflected item-specific information during encoding. In another study, Kuhl and Chun (2014) trained pattern classifiers to discriminate between visual categories (faces vs. scenes, as in the present study) based on activity patterns elicited during the encoding of images and then tested whether these category-related activity patterns were elicited again (reactivated) during image retrieval. Indeed, they found robust evidence for reactivation of visual category information in vPPC. While the study by Kuhl and Chun (2014) was focused on information content at retrieval, the fact that a pattern classifier trained on encoding data successfully transferred to retrieval data indicates that vPPC activity patterns at encoding 1) reflected encoded content and 2) that content-sensitive activity patterns were reinstated with

successful retrieval. Moreover, by comparing vPPC activity patterns elicited during image retrieval to those elicited during image perception, Kuhl and Chun (2014) also found evidence for item-specific information within vPPC (e.g., which face was being retrieved), complementing the findings of Xue et al. (2012).

Here, by relating the strength of pattern-based information at encoding to subsequent remembering (Kuhl et al. 2012), we clearly show—across 2 independent data sets—that activity patterns in vPPC not only reflected the contents of encoding, but that the strength of information in vPPC was diagnostic of successful encoding. Critically, this positive pattern-based subsequent memory effect was present within the same vPPC subregions that exhibited negative univariate subsequent memory effects. Thus, despite the fact that vPPC exhibits strongly negative subsequent memory effects, our findings—combined with prior findings—provide unambiguous evidence that vPPC activity patterns elicited during event encoding contain information about what is being encoded and this pattern-based information is highly predictive of successful remembering.

### Negative Relationship Between Univariate Amplitude and Pattern-Based Information

The fact that vPPC exhibited a negative univariate subsequent memory effect as well as a positive pattern-based subsequent memory effect constitutes a striking dissociation between these measures. However, in contrast to examples where pattern-based analyses are sensitive to information that is not reflected in univariate measures (Harrison and Tong 2009; Sreenivasan et al. 2014) or examples where pattern-based information and univariate measures track different phenomena (Jimura and Poldrack 2012; Moore et al. 2013; Ward et al. 2013), our results suggest that pattern-based information and univariate amplitude co-varied, but that the direction of this relationship was negative, not positive. Specifically, we observed a negative trial-by-trial

relationship between univariate activity and pattern-based information within vPPC, which sharply contrasts with the positive relationship between these measures that we observed in VTC.

At least two prior studies have also reported negative relationships between univariate amplitude and pattern-based information (Kok et al. 2012; Aly and Turk-Browne 2015). Kok and colleagues (2012) found that when the orientation of a visual grating was predicted by an auditory cue, this resulted in reduced univariate responses—but better decoding of the orientation—in early visual cortex. Similarly, Aly and Turk-Browne (2015) recently found that univariate hippocampal activity was lower when subjects attended to the spatial layout of a room, compared with an object within the room, but that pattern-based information related to the locus of attention was stronger in the spatial layout than object condition. Both of these studies suggested that sharper or sparser neural representations were likely to underlie the dissociation between univariate activation and distributed pattern-based information. Indeed, Kok et al. (2012) found that the expectation-induced reduction of univariate amplitude was strongest in voxels that were not tuned to the stimulus orientation. Consistent with this observation, we found that univariate reductions in vPPC that predicted subsequent remembering were most apparent in voxels not tuned to the visual category of the to-be-encoded stimulus. For example, negative subsequent memory effects for scenes were relatively more apparent in vPPC voxels that did not show a strong preference for scenes. This observation is reminiscent of the proposal that sharpening is a mechanism underlying visual priming (Desimone 1996); however, in the present study there was no repetition of encoding stimuli or any implicit learning. Thus, despite surface similarity, our results are not obviously related to sharpening as it has been discussed in the context of visual priming and adaptation (Grill-Spector et al. 2006).

One potential explanation for the negative relationship between univariate amplitude and pattern-based information is that lower univariate amplitude reflects higher signal-to-noise ratios. In particular, because vPPC tended to be deactivated during encoding, relative to baseline, greater univariate decreases could be recast in terms of a higher deflection from baseline. By this account, it is the deflection from baseline, rather than signed activation, that increases pattern-based information. However, we found that the correlation between univariate amplitude and classifier evidence remained numerically negative even within the subset of subjects that exhibited numerically positive (above baseline) univariate responses in vPPC. Thus, the negative relationship between univariate amplitude and pattern-based information is not easily accounted for in terms of deflection from baseline.

Better understanding the negative relationship between univariate amplitude and pattern-based information in vPPC during encoding will require further investigations. However, our findings do suggest experimental manipulations that would help to adjudicate between different interpretations. As noted above, a common interpretation of vPPC activity during encoding is that it is (positively) related to off-task processing (Uncapher and Wagner 2009; Kim et al. 2010; Cabeza et al. 2012). For example, vPPC exhibits increased activation to external stimuli that trigger bottom-up capture of attention (Corbetta et al. 2008), and negative univariate subsequent memory effects have been shown to overlap, anatomically, with bottom-up attentional orienting effects (Uncapher et al. 2011). Thus, lower vPPC activity during encoding can be interpreted in terms of lower distraction from irrelevant sources of information and, therefore, better encoding. An informative manipulation to potentially reconcile this

perspective with the current findings would be to include an encoding display that contained both a target (to-be-encoded) stimulus as well as a salient distractor. Pattern-based analyses, as in the present study, could test whether vPPC activity patterns reflect the distractor stimulus and, in particular, whether successful encoding of the target is best explained in terms of decreased representation of the distractor. Notably, this perspective is conceptually similar to the proposal that vPPC activity reductions at encoding reflect “efficient suppression” of information unrelated to the to-be-encoded stimulus (Vannini et al. 2013).

### What Is the Nature of vPPC Representations?

Our findings add to several observations that vPPC activity patterns reflect what is being remembered (Xue et al. 2012; Kuhl et al. 2013; Kuhl and Chun 2014; St-Laurent et al. 2015), but these findings naturally raise the question of how or why vPPC activity patterns reflect mnemonic content. Because multi-voxel pattern classification is sensitive to many different signals that covary with experimental conditions (Davis and Poldrack 2013), successful decoding of stimulus information in vPPC could either reflect “active representation” of encoded (or retrieved) information or cognitive processes or operations that are differentially engaged according to the type of stimulus being encoded. Of course, the distinction between these possibilities may not be categorical and even “active representation” encompasses distinct possibilities: for example, vPPC representations may be perceptual, semantic, or affective in nature—or some combination of information sources.

Beyond the domain of memory, a number of neuroimaging studies have found that the angular gyrus is involved in semantic processing (for reviews, see Binder and Desai 2011; Seghier 2013). In particular, angular gyrus may be important for processing relatively complicated semantic structure, as is involved in sentence-level processing (Humphreys and Ralph 2015). Likewise, it has been argued that angular gyrus plays a high-level role in integrating information that is accumulated over relatively long time-scales—for example, understanding an entire conversation, as opposed to a single word (Hasson et al. 2015). According to one recent proposal that is specifically related to episodic memory, angular gyrus plays a critical role in integrating information from diverse neural sources to create a bound event representation (Shimamura 2011). This perspective is partly motivated by the anatomical connectivity of vPPC, which suggests that angular gyrus is a “convergence zone” (Binder and Desai 2011), with input from multiple perceptual systems. To the extent that vPPC receives diverse sources of information, this could explain why vPPC involvement in memory operations generalizes across different types of content (Buckner and Wheeler 2001), but the diversity of input may also give rise to distinctive, event-specific vPPC activity patterns, which could explain why pattern-based analyses of vPPC have yielded high sensitivity to the specific contents of encoding/retrieval (Xue et al. 2012; Kuhl and Chun 2014).

While vPPC was a region of a priori interest in the present study, it is also notable that we observed qualitatively similar results in other regions that have previously been associated with negative univariate subsequent memory effects (see [Supplementary Fig. 4](#)). Namely, voxels in medial prefrontal cortex and medial parietal cortex that exhibited negative univariate subsequent memory effects supported robust category classification ( $P_s < 0.001$ ) and exhibited significant pattern-based subsequent memory effects ( $P_s < 0.01$ ). These regions, along with vPPC, are part of the brain’s so-called default mode network (Shulman

et al. 1997; Yeo et al. 2011). While beyond the scope of the present work, an important question for future work is to establish how/whether the representations formed by vPPC differ from those in other default mode regions, including medial prefrontal and parietal cortices.

### Relationship Between vPPC Involvement in Encoding and Retrieval

There is a growing appreciation for the fact that lateral parietal cortex contributes to episodic memory (Wagner et al. 2005; Cabeza et al. 2008; Hutchinson et al. 2009; Uncapher and Wagner 2009; Berryhill 2012). However, with respect to vPPC, more attention has been paid to its role in memory retrieval than memory encoding, given the standard finding that encoding activity in vPPC negatively predicts subsequent remembering (Daselaar et al. 2009; Kim 2011), whereas retrieval activity in vPPC is generally positively related to successful remembering (“retrieval success effects”) (Vilberg and Rugg 2009; Hutchinson et al. 2014). Retrieval success effects are particularly apparent in angular gyrus when retrieval involves recall of event details such as the source or context in which information was encoded (Wagner et al. 2005; Hutchinson et al. 2014). The fact that angular gyrus activity positively scales with successful recall as well as various forms of semantic processing, as described above, has led to the suggestion that angular gyrus plays a more general role in retrieving conceptual knowledge (Binder and Desai 2011).

To the extent that vPPC supports the retrieval of conceptual information and/or integration of converging sources of information, one interpretation of negative univariate subsequent memory effects in vPPC is that focusing attention on specific perceptual attributes of to-be-encoded stimulus in the environment gates the retrieval of conceptual information or of integrative processing. This speculation leads to an interesting prediction: in contexts where the encoding of an item might benefit from retrieval and/or integration of related information, then subsequent memory effects in vPPC should “flip” and become positive. A specific situation where this might be expected is in cases where memory is tested via free recall. In free recall, it has been argued that encoding an item as part of a broader context, including representations of temporally adjacent experiences, will increase the likelihood of successful free recall (Polyn et al. 2009). Indeed, while the overwhelming majority of vPPC subsequent memory effects are negative, there are a handful of examples of positive vPPC subsequent memory effects when memory is measured via free recall (Staresina and Davachi 2006; Xue et al. 2012; Burke et al. 2014). In a targeted comparison of item recognition versus free recall tests, Staresina and Davachi (2006) found that a positive subsequent memory effect was selectively present in vPPC when memory was tested via free recall; when subsequent memory was tested via item recognition, the subsequent memory effect was numerically negative and significantly different from the subsequent memory effect based on free recall. Thus, activity patterns in vPPC may reflect mnemonic contents during encoding and retrieval, with the amplitude of the vPPC encoding response reflecting the degree to which “internal” conceptual information is retrieved. Whether or not vPPC amplitude predicts subsequent remembering will depend on the specific conceptual information that is retrieved and its relevance to the kind of memory test that is ultimately employed.

One important issue that constrains proposed contributions of vPPC to either encoding or retrieval is that damage to vPPC is typically associated with modest memory impairments or even

no impairment at all (Ally et al. 2008; Haramati et al. 2008). However, evidence for spared memory performance in parietal lobe patients has largely come from studies using simple recognition tasks. In contrast, vPPC damage has been shown to significantly impair paired-associate cued recall (the same form of memory studied here) (Ben-Zvi et al. 2015) and also influences subjective expressions of memory confidence (Simons et al. 2010; Hower et al. 2014). Similarly, targeted stimulation of vPPC has been shown to influence subjective (Sestieri et al. 2013; Yazar et al. 2014) and objective (Wang et al. 2014) measures of memory. Thus, while vPPC damage clearly does not produce dense amnesia, patient and stimulation studies do support the idea that vPPC plays a functional role in memory. Our findings further inform current debates by showing that vPPC activity is not a content-free index of attentional orienting (Cabeza et al. 2012), but is a content-rich reflection of mnemonic processing. By making use of pattern-based analyses like those employed in the present study, future studies will further clarify how vPPC contributes to encoding (and retrieval) by specifying the information that is—or is not—selected for processing.

### Supplementary Material

Supplementary material can be found at: <http://www.cercor.oxfordjournals.org/>.

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### Notes

*Conflict of Interest:* None declared.

### References

- Ally BA, Simons JS, McKeever JD, Peers PV, Budson AE. 2008. Parietal contributions to recollection: electrophysiological evidence from aging and patients with parietal lesions. *Neuropsychologia*. 46:1800–1812.
- Aly M, Turk-Browne NB. 2015. Attention stabilizes representations in the human hippocampus. *Cereb Cortex*. doi: 10.1093/cercor/bhv041.
- Ben-Zvi S, Soroker N, Levy DA. 2015. Parietal lesion effects on cued recall following pair associate learning. *Neuropsychologia*. 73:176–194.
- Berryhill ME. 2012. Insights from neuropsychology: pinpointing the role of the posterior parietal cortex in episodic and working memory. *Front Integr Neurosci*. 6; doi: 10.3389/fnint.2012.00031.
- Binder JR, Desai RH. 2011. The neurobiology of semantic memory. *Trends Cogn Sci*. 15:527–536.
- Brewer JB, Zhao Z, Desmond JE, Glover GH, Gabrieli JDE. 1998. Making memories: brain activity that predicts how well visual experience will be remembered. *Science*. 281:1185–1187.
- Buckner RL, Andrews-Hanna JR, Schacter DL. 2008. The brain’s default network. *Ann NY Acad Sci*. 1124:1–38.
- Buckner RL, Wheeler ME. 2001. The cognitive neuroscience of remembering. *Nat Rev Neurosci*. 2:624–634.
- Burke JF, Long NM, Zaghoul KA, Sharan AD, Sperling MR, Kahana MJ. 2014. Human intracranial high-frequency activity maps episodic memory formation in space and time. *NeuroImage*. 85:834–843.

- Cabeza R, Ciaramelli E, Moscovitch M. 2012. Cognitive contributions of the ventral parietal cortex: an integrative theoretical account. *Trends Cogn Sci*. 16:338–352.
- Cabeza R, Ciaramelli E, Olson IR, Moscovitch M. 2008. The parietal cortex and episodic memory: an attentional account. *Nat Rev Neurosci*. 9:613–625.
- Christoff K, Gordon AM, Smallwood J, Smith R, Schooler JW. 2009. Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc Natl Acad Sci*. 106:8719–8724.
- Corbetta M, Patel G, Shulman GL. 2008. The reorienting system of the human brain: from environment to theory of mind. *Neuron*. 58:306–324.
- Corbetta M, Shulman GL. 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nat Rev Neurosci*. 3:201–215.
- Daselaar SM, Prince SE, Cabeza R. 2004. When less means more: deactivations during encoding that predict subsequent memory. *NeuroImage*. 23:921–927.
- Daselaar SM, Prince SE, Dennis NA, Hayes SM, Kim H, Cabeza R. 2009. Posterior midline and ventral parietal activity is associated with retrieval success and encoding failure. *Front Hum Neurosci*. 3; doi: 10.3389/fnhum.2009.013.2009.
- Davis T, Poldrack RA. 2013. Measuring neural representations with fMRI: practices and pitfalls. *Ann NY Acad Sci*. 1296:108–134.
- Desimone R. 1996. Neural mechanisms for visual memory and their role in attention. *Proc Natl Acad Sci*. 93:13494–13499.
- Fernández G, Tendolkar I. 2001. Integrated brain activity in medial temporal and prefrontal areas predicts subsequent memory performance: human declarative memory formation at the system level. *Brain Res Bull*. 55:1–9.
- Gilmore AW, Nelson SM, McDermott KB. 2015. A parietal memory network revealed by multiple MRI methods. *Trends Cogn Sci*. 19:534–543.
- Grill-Spector K, Henson R, Martin A. 2006. Repetition and the brain: neural models of stimulus-specific effects. *Trends Cogn Sci*. 10:14–23.
- Haramati S, Soroker N, Dudai Y, Levy DA. 2008. The posterior parietal cortex in recognition memory: a neuropsychological study. *Neuropsychologia*. 46:1756–1766.
- Harrison SA, Tong F. 2009. Decoding reveals the contents of visual working memory in early visual areas. *Nature*. 458:632–635.
- Hasson U, Chen J, Honey CJ. 2015. Hierarchical process memory: memory as an integral component of information processing. *Trends Cogn Sci*. 19:304–313.
- Hower KH, Wixted J, Berryhill ME, Olson IR. 2014. Impaired perception of mnemonic oldness, but not mnemonic newness, after parietal lobe damage. *Neuropsychologia*. 56:409–417.
- Huijbers W, Vannini P, Sperling RA, Pennartz CM, Cabeza R, Daselaar SM. 2012. Explaining the encoding/retrieval flip: memory-related deactivations and activations in the postero-medial cortex. *Neuropsychologia*. 50:3764–3774.
- Humphreys GF, Ralph MAL. 2015. Fusion and fission of cognitive functions in the human parietal cortex. *Cereb Cortex*. 25:3547–3560.
- Hutchinson JB, Uncapher MR, Wagner AD. 2009. Posterior parietal cortex and episodic retrieval: convergent and divergent effects of attention and memory. *Learn Mem*. 16:343–356.
- Hutchinson JB, Uncapher MR, Weiner KS, Bressler DW, Silver MA, Preston AR, Wagner AD. 2014. Functional heterogeneity in posterior parietal cortex across attention and episodic memory retrieval. *Cereb Cortex*. 24:49–66.
- Jimura K, Poldrack RA. 2012. Analyses of regional-average activation and multivoxel pattern information tell complementary stories. *Neuropsychologia*. 50:544–552.
- Kim G, Lewis-Peacock JA, Norman KA, Turk-Browne NB. 2014. Pruning of memories by context-based prediction error. *Proc Natl Acad Sci*. 111:8997–9002.
- Kim H. 2011. Neural activity that predicts subsequent memory and forgetting: a meta-analysis of 74 fMRI studies. *NeuroImage*. 54:2446–2461.
- Kim H, Daselaar SM, Cabeza R. 2010. Overlapping brain activity between episodic memory encoding and retrieval: roles of the task-positive and task-negative networks. *NeuroImage*. 49:1045–1054.
- Kok P, Jehee JFM, de Lange FP. 2012. Less is more: expectation sharpens representations in the primary visual cortex. *Neuron*. 75:265–270.
- Kuhl BA, Chun MM. 2014. Successful remembering elicits event-specific activity patterns in lateral parietal cortex. *J Neurosci*. 34:8051–8060.
- Kuhl BA, Johnson MK, Chun MM. 2013. Dissociable neural mechanisms for goal-directed versus incidental memory reactivation. *J Neurosci*. 33:16099–16109.
- Kuhl BA, Rissman J, Chun MM, Wagner AD. 2011. Fidelity of neural reactivation reveals competition between memories. *Proc Natl Acad Sci*. 108:5903–5908.
- Kuhl BA, Rissman J, Wagner AD. 2012. Multi-voxel patterns of visual category representation during episodic encoding are predictive of subsequent memory. *Neuropsychologia*. 50:458–469.
- Mason MF, Norton MI, Van Horn JD, Wegner DM, Grafton ST, Macrae CN. 2007. Wandering minds: the default network and stimulus-independent thought. *Science*. 315:393–395.
- Moore KS, Yi D-J, Chun M. 2013. The effect of attention on repetition suppression and multivoxel pattern similarity. *J Cogn Neurosci*. 25:1305–1314.
- Norman KA, Polyn SM, Detre GJ, Haxby JV. 2006. Beyond mind-reading: multi-voxel pattern analysis of fMRI data. *Trends Cogn Sci*. 10:424–430.
- Otten LJ, Rugg MD. 2001. When more means less: neural activity related to unsuccessful memory encoding. *Curr Biol*. 11:1528–1530.
- Paller KA, Wagner AD. 2002. Observing the transformation of experience into memory. *Trends Cogn Sci*. 6:93–102.
- Polyn SM, Norman KA, Kahana MJ. 2009. A context maintenance and retrieval model of organizational processes in free recall. *Psychol Rev*. 116:129–156.
- Seghier ML. 2013. The angular gyrus: multiple functions and multiple subdivisions. *Neuroscientist*. 19:43–61.
- Sestieri C, Capotosto P, Tosoni A, Luca Romani G, Corbetta M. 2013. Interference with episodic memory retrieval following transcranial stimulation of the inferior but not the superior parietal lobule. *Neuropsychologia*. 51:900–906.
- Shimamura AP. 2011. Episodic retrieval and the cortical binding of relational activity. *Cogn Affect Behav Neurosci*. 11:277–291.
- Shulman GL, Astafiev SV, McAvoy MP, d'Avossa G, Corbetta M. 2007. Right TPJ deactivation during visual search: functional significance and support for a filter hypothesis. *Cereb Cortex*. 17:2625–2633.
- Shulman GL, Fiez JA, Corbetta M, Buckner RL, Miezin FM, Raichle ME, Petersen SE. 1997. Common blood flow changes across visual tasks: II. Decreases in cerebral cortex. *J Cogn Neurosci*. 9:648–663.

- Simons JS, Peers PV, Mazuz YS, Berryhill ME, Olson IR. 2010. Dissociation between memory accuracy and memory confidence following bilateral parietal lesions. *Cereb Cortex*. 20:479–485.
- Smith AT, Kossilo P, Williams AL. 2011. The confounding effect of response amplitude on MVPA performance measures. *NeuroImage*. 56:525–530.
- Sreenivasan KK, Vytlačil J, D'Esposito M. 2014. Distributed and dynamic storage of working memory stimulus information in extrastriate cortex. *J Cogn Neurosci*. 26:1141–1153.
- Staresina BP, Davachi L. 2006. Differential encoding mechanisms for subsequent associative recognition and free recall. *J Neurosci*. 26:9162–9172.
- St-Laurent M, Abdi H, Buchsbaum BR. 2015. Distributed patterns of reactivation predict vividness of recollection. *J Cogn Neurosci*. 27:2000–2018.
- Tong F, Harrison SA, Dewey JA, Kamitani Y. 2012. Relationship between BOLD amplitude and pattern classification of orientation-selective activity in the human visual cortex. *NeuroImage*. 63:1212–1222.
- Turk-Browne NB, Yi D-J, Chun MM. 2006. Linking implicit and explicit memory: common encoding factors and shared representations. *Neuron*. 49:917–927.
- Tzourio-Mazoyer N, Landeau B, Papathanassiou D, Crivello F, Etard O, Delcroix N, Mazoyer B, Joliot M. 2002. Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *NeuroImage*. 15:273–289.
- Uncapher MR, Hutchinson JB, Wagner AD. 2011. Dissociable effects of top-down and bottom-up attention during episodic encoding. *J Neurosci*. 31:12613–12628.
- Uncapher MR, Wagner AD. 2009. Posterior parietal cortex and episodic encoding: insights from fMRI subsequent memory effects and dual-attention theory. *Neurobiol Learn Mem*. 91:139–154.
- Vannini P, Hedden T, Huijbers W, Ward A, Johnson KA, Sperling RA. 2013. The ups and downs of the posteromedial cortex: age- and amyloid-related functional alterations of the encoding/retrieval flip in cognitively normal older adults. *Cereb Cortex*. 23:1317–1328.
- Vannini P, O'Brien J, O'Keefe K, Pihlajamäki M, LaViolette P, Sperling RA. 2011. What goes down must come up: role of the posteromedial cortices in encoding and retrieval. *Cereb Cortex*. 21:22–34.
- Vilberg KL, Rugg MD. 2009. Functional significance of retrieval-related activity in lateral parietal cortex: evidence from fMRI and ERPs. *Hum Brain Mapp*. 30:1490–1501.
- Wagner AD, Davachi L. 2001. Cognitive neuroscience: forgetting of things past. *Curr Biol*. 11:R964–R967.
- Wagner AD, Schacter DL, Rotte M, Koutstaal W, Maril A, Dale AM, Rosen BR, Buckner RL. 1998. Building memories: remembering and forgetting of verbal experiences as predicted by brain activity. *Science*. 281:1188–1191.
- Wagner AD, Shannon BJ, Kahn I, Buckner RL. 2005. Parietal lobe contributions to episodic memory retrieval. *Trends Cogn Sci*. 9:445–453.
- Wang JX, Rogers LM, Gross EZ, Ryals AJ, Dokucu ME, Brandstatt KL, Hermiller MS, Voss JL. 2014. Targeted enhancement of cortical-hippocampal brain networks and associative memory. *Science*. 345:1054–1057.
- Ward EJ, Chun MM, Kuhl BA. 2013. Repetition suppression and multi-voxel pattern similarity differentially track implicit and explicit visual memory. *J Neurosci*. 33:14749–14757.
- Xue G, Dong Q, Chen C, Lu Z-L, Mumford JA, Poldrack RA. 2012. Complementary role of frontoparietal activity and cortical pattern similarity in successful episodic memory encoding. *Cereb Cortex*. 23:1562–1571.
- Yazar Y, Bergström ZM, Simons JS. 2014. Continuous theta burst stimulation of angular gyrus reduces subjective recollection. *PLoS ONE*. 9:e110414.
- Yeo BTT, Krienen FM, Sepulcre J, Sabuncu MR, Lashkari D, Hollinshead M, Roffman JL, Smoller JW, Zöllei L, Polimeni JR, et al. 2011. The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *J Neurophysiol*. 106:1125–1165.