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Word frequency and subsequent memory effects studied using event-related fMRI

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Abstract

Event-related fMRI was used to evaluate the effect of printed word frequency on the subsequent recognition of words incidentally encoded while 16 healthy right-handed volunteers performed living/nonliving judgments. Semantic judgment took longer for low-frequency words. These words were more accurately recognized than high-frequency words at later testing. Low-frequency words were also associated with relatively greater left prefrontal, left fusiform gyrus, and anterior cingulate activation. Words that were subsequently recognized were associated with greater activation in the left prefrontal region compared to those that were forgotten. These findings suggest the specific brain regions where less commonly encountered words are processed in a manner that facilitates their subsequent recognition.

Keywords: fMRI; Subsequent memory; Word frequency; Learning

Introduction

Learning can be defined as the assimilation of information that results in an enduring change in behavior. How and where this assimilation occurs in the brain are key issues in the cognitive neuroscience of language acquisition. Of specific interest to the present work is how the brain might process less frequently encountered concrete words in a way that makes them less effortful to process in subsequent encounters.

In previous work (Chee et al., 2001), an inverse relationship was observed between proficiency in language and magnitude of left prefrontal activation as measured by BOLD signal change. Less left prefrontal activation and shorter response times were observed when bilinguals made associative semantic judgments in the language that they were more proficient in compared to their less proficient second language.

Greater proficiency in a particular language may simply be a result of higher exposure to the words of that language. Printed word frequency, an index of how much exposure people have had to a word (Kucera and Francis, 1967), might therefore be expected to show a relationship to BOLD signal change that reflects relative language proficiency. In support of this notion, an effect of word frequency on cortical activation during a semantic judgment task was found (Chee et al., 2002) whereby there was less prefrontal activation with high-frequency words compared to low-frequency words. We suggested that this could reflect the greater ease with which semantic information about high-frequency words is retrieved relative to information related to low-frequency words.

Interestingly, subjects are better able to subsequently recognize low-frequency (as compared to high-frequency) words as having appeared in a mixed list of studied words (Gardiner and Java, 1990). Furthermore, low-frequency novel words are less likely to yield false alarms relative to high-frequency novel words (Glanzer and Adams, 1990). To account for these observations, it has been suggested that more lexical features and contextual information (Guttentag and Carroll, 1998) are considered during the presentation of low-frequency words (Guttentag and Carroll, 1998).

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Table 1
Characteristics of word stimuli used

Word frequency (number of words)	Living/nonliving (number of words)	Mean word frequency (SD)	Median word frequency	Mean word length (SD)	Number of irregular words
High (96)	Living (48)	72.9 (66.6)	50	5.56 (1.75)	12
	Nonliving (48)	71.4 (60.1)	50	5.23 (1.52)	10
Low (96)	Living (48)	2.35 (1.30)	2	5.40 (1.67)	8
	Nonliving (48)	2.5 (1.30)	2	5.23 (1.52)	9

Note. Word frequency is expressed in number of occurrences per million words. SD, standard deviation.

Words confidently recognized as having been seen previously were associated with greater blood flow change at encoding in the left prefrontal cortex and parahippocampal region compared to words that were subsequently forgotten (Wagner et al., 1998; Kirchhoff et al., 2000). These subsequent memory effects may reflect a deeper processing of words at study that is conducive to retrieval during a subsequent memory test (Rugg, 1995). Consistent with this notion, better subsequent recognition performance and greater activation in the left ventral inferior frontal gyrus and anterior hippocampus were observed when subjects made living/nonliving decisions (reflecting “deeper” semantic processing) compared to when they made alphabetical decisions (reflecting more “shallow” perceptual processing) on words at encoding (Otten et al., 2001).

In order to evaluate the mechanism(s) by which the brain processes less commonly encountered words in a way that promotes their subsequent retrieval, the current study utilized event-related fMRI to examine cortical activation in volunteers engaged in an implicit encoding task (living/nonliving judgment) involving high- and low-frequency words. Subjects later took a recognition test and these results were used to sort cortical responses to these high- and low-frequency words according to subsequent memory performance. We expected low-frequency words to be better recognized at test and at encoding, they would be associated with higher BOLD signal in the left prefrontal cortex. We also sought to characterize the extent to which word frequency contributes to subsequent memory. If subsequent memory effects were simply determined by differences in word frequency, there would be no difference in BOLD response between remembered or forgotten words of the same frequency. However, if subsequent memory effects were to be evident with high- and low-frequency words, this would indicate that while word frequency can influence subsequent memory performance, other factors determine recognition performance as well.

Methods

Subjects

Sixteen neurologically normal, right-handed subjects (9 women) aged between 20 and 25 years gave informed consent for this study. Subjects were selected on the basis of good performance in standardized English examinations described previously (Chee et al., 2002).

Living/nonliving judgment task (fMRI)

Words used to create the stimuli were obtained from the MRC Psycholinguistic Database (http://www.psy.uwa.edu.au/MRCDatabase/uwa_mrc.htm). The word list for living/nonliving judgments contained 192 words classified (48 words in each category) into high-frequency living things, high-frequency nonliving things, low-frequency living things, and low-frequency nonliving things (Table 1).

After a briefing and an out-of-scanner trial run, subjects performed living/ nonliving judgments on single words in an event-related fMRI experiment. They were instructed to determine if each presented word denoted a living or nonliving entity and respond accordingly with a mouse-button press.

Each subject underwent six runs of fMRI scans with 148 sets of functional images collected in each run. Eight words from each category were pseudo-randomly presented in each run. Each stimulus appeared for 2 s with stimulus onset asynchronies (SOA: the time interval between the onset of successive stimuli) of 6, 8, 10, or 12 s. The minimum SOA was kept relatively high in order to allow for adequate signal recovery between consecutive stimuli. Multiple SOAs were used to generate enough equations to solve for each predictor during the analysis of functional data (Miezin et al., 2000). Following a response, the stimulus was replaced by a fixation crosshair until the next stimulus appeared. The order of runs was counterbalanced across subjects.

Recognition task (outside scanner)

For the recognition task, an additional list of novel words was generated that matched the originally presented list in the distribution of word frequency and animacy. The resulting word list for the recognition test comprised 192 old and 192 novel words.

Approximately 24 h after performing the incidental encoding task, subjects took the recognition test. They judged single words as either previously seen in the encoding task (OLD) or novel (NEW) with either high (HC) or low (LC) confidence. Each stimulus appeared for a maximum duration of 3.5 s; SOA was 4 s. Following a response, the test stimulus was replaced by a fixation crosshair until the next stimulus appeared.

Imaging protocol

fMRI experiments were performed in a 2.0 T Bruker Tomikon S200 system (Bruker, Karlsruhe, Germany). A blipped gradient-echo EPI sequence was used for functional imaging with a TR of 2000 ms, a FOV of 23 × 23 cm and a 128 × 64 pixel matrix. Fifteen oblique axial slices approximately parallel to the AC-PC line and 4 mm thick (2 mm gap) were acquired. High-resolution coplanar T2 anatomical images were also obtained. A high-resolution anatomical reference image was acquired using a 3D-SPGR sequence. A bite-bar was used to reduce head motion.

Following phase correction, the functional images were analyzed using BrainVoyager 2000 software version 4.6 (Brain Innovation, Maastricht, Holland). Intensity normalization was performed prior to motion correction. The coplanar T2 images were then used to register the functional data set to the 3-D image. The resulting realigned data set was transformed into Talairach space (Talairach and Tournoux, 1988). Gaussian filtering was applied, in the spatial domain, with a smoothing kernel of 8 mm FWHM for the computation of group-level activation maps.

Behavioral data analysis

Analysis was performed using within-subjects' paired *t* tests; individual cases in which one of the responses in the pair was missing (null response) were excluded from the analysis. One subject's behavioral data at encoding was excluded from this analysis because of a mechanical error.

Responses in the recognition task (OLD or NEW, with HC or LC) were classified as "hits" (correctly identifying an old word as OLD), "misses" (incorrectly identifying an old word as NEW), "false alarms" (identifying a new word as OLD), and "correct rejections" (identifying a new word as NEW).

Image data analysis

Image data analyses were performed at the group or multisubject level. Three separate general linear models (GLMs) were used to analyze the imaging data. These sought to elucidate the word frequency effect, the subsequent memory effect, and the effect of word frequency on response time. The GLM for the analysis of the word frequency effect in the functional data considered word frequency as the only explanatory variable. Encoding events were sorted into two conditions: high and low word frequency.

The second GLM used word frequency, memorability, and decision confidence as explanatory variables. Encoding events were sorted into two conditions for each of the three variables: low and high word frequency, remembered and forgotten words, and high and low confidence judgments.

Table 2
Data from 15 subjects (1 subject excluded) showing the proportion of correct responses and mean response times for living/nonliving judgments performed on high- and low-frequency words at encoding

Frequency	Proportion correct mean (SD)	Response time (s) mean (SD)
High	0.954 (0.024)	0.816 (0.127)
Low	0.917 (0.071)	0.911 (0.139)

Note. Standard deviations (SD) are shown in parentheses.

The third GLM used word frequency and response time as explanatory variables. To distinguish the effects of word frequency and response time on activation during encoding, events were divided on the basis of the median response time during the encoding task for each subject for both levels of word frequency. Events that were faster or equal to the median response time for that subject were classified as "short response time." Encoding events were sorted into four conditions: low and high word frequency with either short or long response times.

Hemodynamic responses to the different event classes (e.g., low-frequency words, high-frequency words) were obtained using deconvolution (Miezin et al., 2000). Eight predictors were used to determine the signal time course of each event type. A voxel was considered activated if it was above threshold by assessing the contribution of the third, fourth, and fifth predictors (corresponding to the peak of the BOLD response) in each event condition. A corrected threshold of $P < 0.01$ was used. Regions in the multisubject activation map selected for analysis were those that contained voxels that showed a significant difference ($P < 0.005$ uncorrected) in activation between conditions of interest (e.g., low frequency > high frequency). ROI analysis was then performed on voxels jointly active in the conditions of interest. For example, if word frequency was the variable of interest, voxels in the region jointly activated by high- and low-frequency words were selected for the comparison of signal change elicited by words of each frequency category. Voxels contributing to each ROI lay within a bounding cube of edge 15 mm surrounding the activation peak for that ROI.

Results

Word frequency effect

During encoding, subjects were slower [$t(14) = -8.09$, $P < 0.01$] and less accurate [$t(14) = 2.50$, $P < 0.05$] at making living/nonliving judgments involving low-frequency words compared to high-frequency words (Table 2).

Regions activated when subjects made living/nonliving

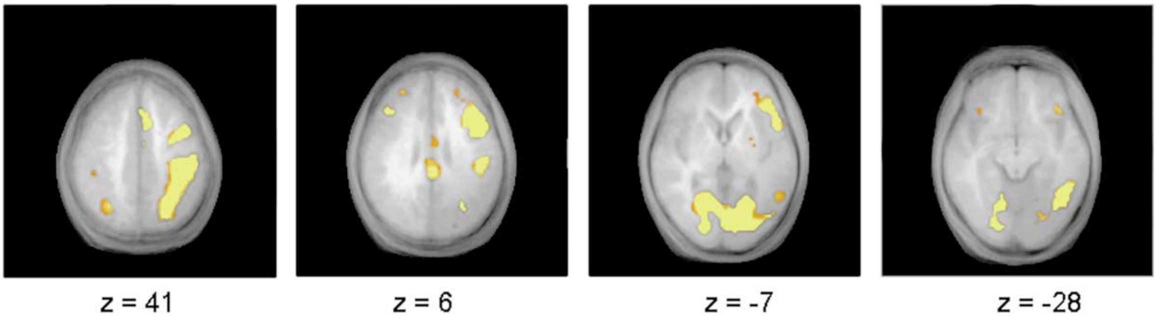

Fig. 1. Axial slices showing brain regions activated when subjects performed living/nonliving judgments on words. The Talairach coordinate of each section is displayed below each image.

judgments irrespective of word frequency included the left anterior cingulate (BA 32), bilateral inferior frontal regions, with a left hemisphere predominance (BA 9, 44, 46), bilateral superior parietal (BA 7), left inferior temporal (BA 37), bilateral occipital regions (BA 18, 19), and the left primary motor area (BA 6; motor response) (Fig. 1 and Table 3a).

Regions showing the word frequency effect were the left anterior cingulate (BA 32), bilateral inferior frontal regions, with a left-hemisphere predominance (BA 44, 45, 46), and the left inferior temporal region (BA 37) (Fig. 2a and Table 3b).

Subsequent memory effect

During recognition, subjects' performance showed the mirror effect of word frequency (Glanzer and Adams, 1985, 1990) for high confidence judgments in that low-frequency words had a higher proportion of hits [$t(15) = -2.22$, $P < 0.05$] and fewer false alarms [$t(15) = 3.27$, $P < 0.01$] compared to high-frequency words (Fig. 3). This was not so for low confidence judgments.

Subsequently remembered words (hits) were associated with more correct responses than subsequently forgotten words (misses) for both high [$t(14) = 4.92$, $P < 0.01$] and low [$t(14) = 9.57$, $P < 0.01$] frequency words (Fig. 4a). There were no significant differences in subjects' response times during encoding between words that were subsequently remembered and those that were forgotten for either low- [$t(14) = 1.47$, n.s.] or high- [$t(14) = 1.72$, n.s.] frequency words (Fig. 4a). There was a marginal trend for remembered words to be associated with longer response times at encoding; this reached significance in subsequent analyses (see Word frequency and response time analysis below).

A subsequent memory effect was observed in the left inferior frontal region (BA 44) (Fig. 5a and Table 3c) irrespective of the confidence with which memorability judgments were made. Greater activation for remembered words was still evident in responses segregated by frequency, suggesting that other factors, along with word frequency, contribute to subsequent memory. The left anterior cingulate (BA 32) also showed greater activation for remembered words, but only when the judgments were made with low confidence (Fig. 5b and Table 3c). As previous studies have shown that subsequent memory effects are predominantly found for confident hits (Brewer et al., 1998; Wagner et al., 1998; Otten et al., 2001, 2002), we conservatively chose not to ascribe a subsequent memory effect to the anterior cingulate/medial frontal region.

Even with reduced thresholds, we did not detect hippocampal activation at encoding. We note that previous work using animacy judgment has either shown (Otten et al., 2001) or not shown (Otten et al., 2002) hippocampal activation depending on the specific experimental design.

Word frequency and response time

A greater number of hits were associated with long response times [$t(15) = 3.11$, $P < 0.01$]. Conversely, misses were associated with short response times [$t(15) = -3.17$, $P < 0.01$] (Fig. 4b). As low-frequency words were more likely to be remembered, there was an overrepresentation of long responses to low-frequency words. To examine the effect of response time and word frequency alone, some events were randomly excluded as dummy variables in this GLM to allow for a fairer comparison of hemodynamic responses associated with short and long response times.

Words that took longer to process during encoding were associated with greater activation in the left anterior cingulate (BA 32), bilateral inferior frontal regions (with a left hemisphere predominance) (BA 44, 45), and left inferior temporal region (BA 37). Even when response time was taken into consideration, low-frequency words were associated with greater signal change in these regions (Fig. 2b and Table 3d). While there was a broad correspondence of the regions showing the word frequency and response time effects, activation peaks did not overlap completely. Whether or not this implies that related but spatially distinct neural substrates govern these two effects is presently uncertain.

Table 3
Talairach coordinates of activation peaks in the multisubject analyses for (a) living/nonliving judgment, (b) the word frequency contrast, (c) the subsequent memory contrast, and (d) the response time contrast

Brain region	Brodmann's area	*x*	*y*	*z*	*F* value
(a) Living/nonliving judgement					
Left anterior cingulate	32	−4	−2	48	186
Left inferior frontal gyrus	44, 46	−41	18	24	101
Left inferior frontal gyrus	44	−43	7	28	153
Right inferior frontal gyrus	44, 9	43	18	29	85
Left superior parietal region	7	−27	−68	52	38
Right superior parietal region	7	22	−75	51	21
Left inferior temporal region	37	−43	−59	−12	76
Left occipital region	18, 19	−34	−80	−7	69
Left occipital region	18, 19	−28	−83	5	61
Right occipital region	18, 19	20	−83	−3	67
Right occipital region	18, 19	26	−83	11	70
Left primary motor area	4	−40	−18	54	146

(b) Low-frequency words > high-frequency words

Brain region	Brodmann's area	*x*	*y*	*z*	*t* value
Left anterior cingulate	32	−1	16	41	8.6
Left inferior frontal gyrus	44	−40	3	26	6.7
Left inferior frontal gyrus	45	−34	24	6	5.6
Right inferior frontal gyrus	44, 46	41	22	23	5.2
Left inferior temporal region	37	−43	−59	−7	4.5

(c) Remembered words > forgotten words

Brain region	Brodmann's area	*x*	*y*	*z*	*t* value
Left anterior cingulate*	32	−5	13	42	3.5
Left inferior frontal gyrus	44	−37	10	27	4.7

(d) Long response times > short response times

Brain region	Brodmann's area	*x*	*y*	*z*	*t* value
Left anterior cingulate	32	−1	19	42	9.2
Left inferior frontal gyrus	45	−46	17	21	8.9
Left inferior frontal gyrus	47	−44	16	−1	7.8
Right inferior frontal gyrus	46	40	21	24	5.8
Left inferior temporal gyrus	37	−43	−54	−17	4.7

* Low confidence judgements only, see text.

Discussion

The principal finding of the present study is that the relatively greater left prefrontal activity observed with the semantic processing of visually presented low-frequency words compared to high-frequency words is linked to processes that also improve subsequent recognition.

The left prefrontal region is engaged whenever retrieval of knowledge relevant to task-dependent goals is required (Buckner and Wheeler, 2001). In particular tasks that require semantic retrieval result in greater left prefrontal activation compared to tasks that do not require semantic retrieval even when the response times for the latter task are longer (Demb et al., 1995). The magnitude of this activation is greater when the information necessary to make a decision is "harder" to retrieve. This could take the form of less common semantic associations (Fletcher et al., 2000; Wagner et al., 2001), less typical ones (Roskies et al., 2001), or decisions involving words of low print frequency (Chee et al., 2002; Fiebach et al., 2002).

Prior work on the subsequent memory effect has shown that greater left prefrontal activation occurring at the time of encoding is associated with better recognition performance in a subsequent memory task (Wagner et al., 1998; Henson et al., 1999; Kirchhoff et al., 2000; Buckner et al., 2001; Davachi et al., 2001; Otten et al., 2001). Conversely, when prefrontal activation associated with encoding activity is reduced, by interposing a short lag (instead of a long one) between initial and repeat trials (Wagner et al., 2000), or by interposing a secondary distracting task (Fletcher et al.,

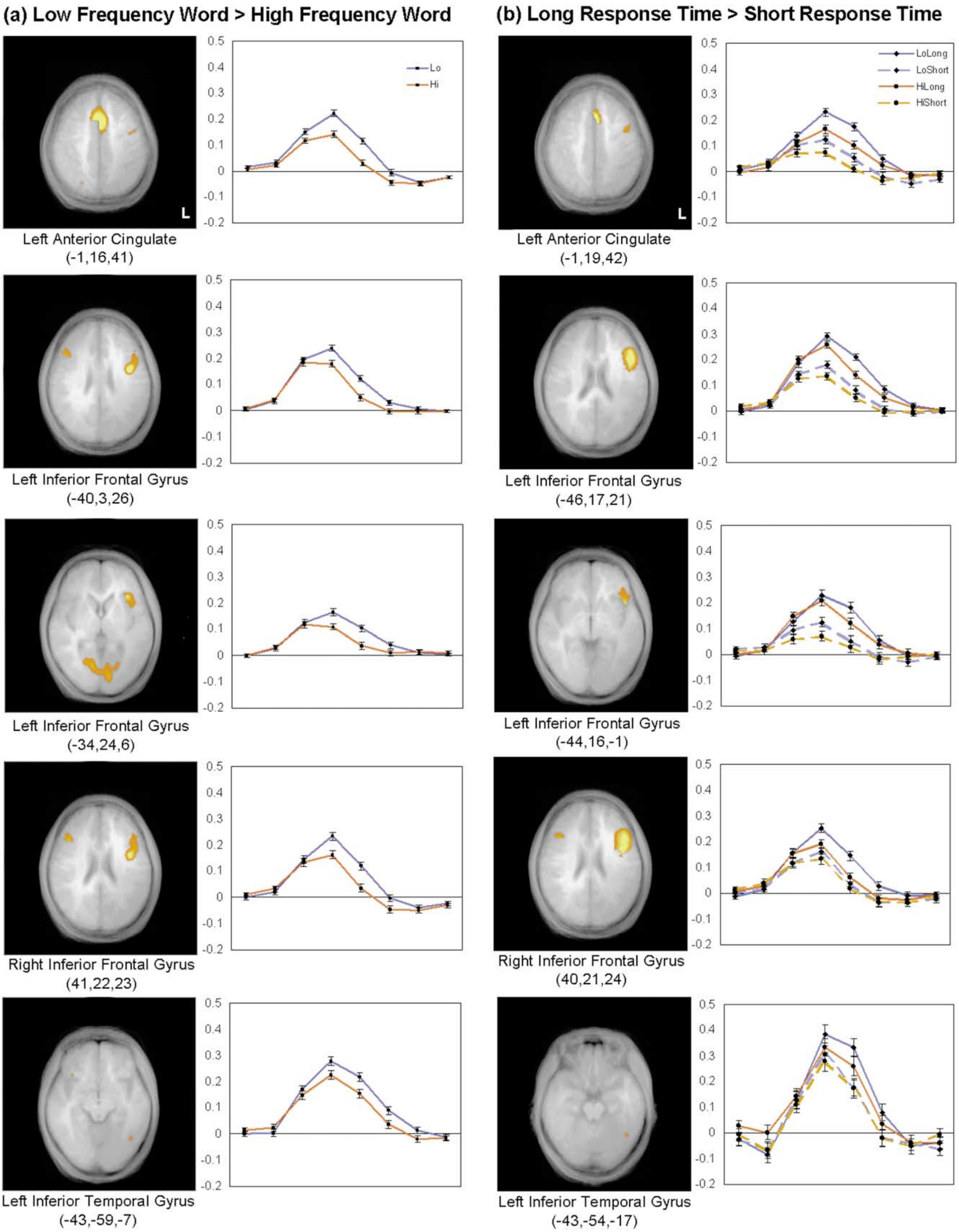

Fig. 2. Axial slices displaying regions showing (a) the word frequency effect alone, and (b) effect of response time and word frequency. Talairach coordinates indicate the activation peaks in each ROI. Lo, low-frequency words; Hi, high-frequency words; Long, long response time; Short, short response time. BOLD signal plots alongside each axial slice show the relative contributions of each condition.

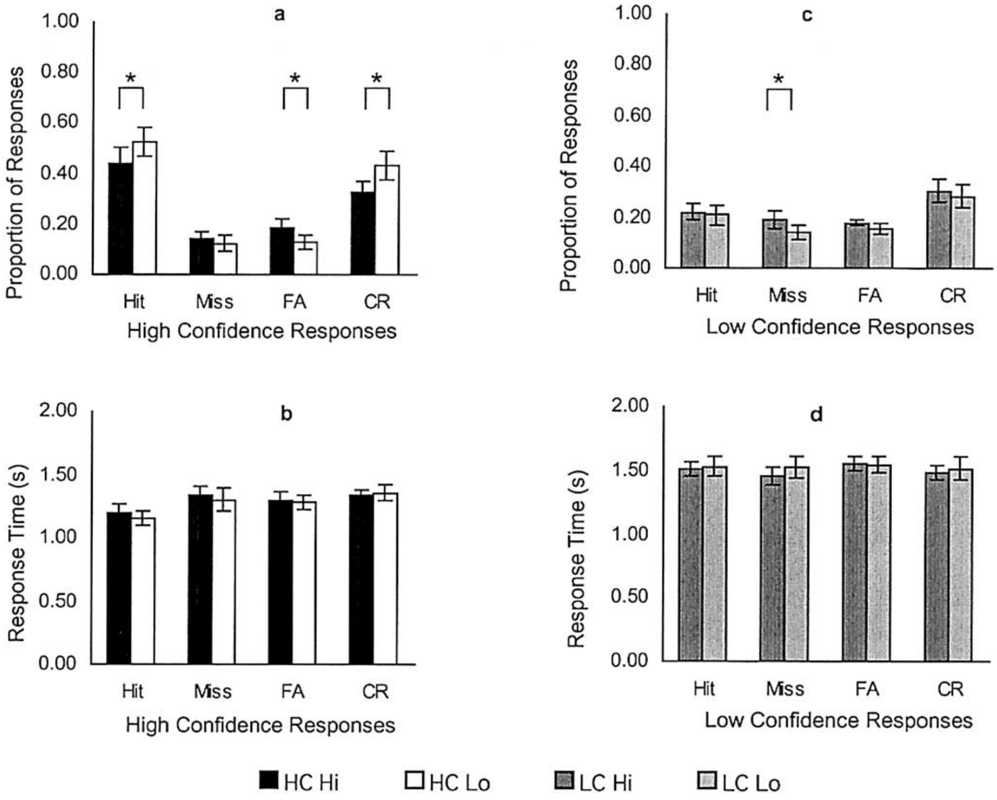

Fig. 3. Proportion of response types and response times for recognition judgements sorted by word frequency and confidence. Hi, high-frequency words; Lo, low-frequency words; HC, high confidence; LC, low confidence; Hit, correctly recognized old words; Miss, unrecognized old words; FA, new words incorrectly recognized as old; CR, correctly rejected new words. Decisions made with high confidence are shown in a and b. Decisions made with low confidence shown in c and d (*denotes within-subjects' significance at $P < 0.05$).

1995), subsequent memory for encoded words is impaired. Thus, it appears that over a range of experimental tasks, whenever the magnitude of left prefrontal activation is increased, better recognition performance is engendered.

In the present study, it appears that the greater difficulty in retrieval of information about low relative to high-frequency words (indexed by longer response times, lower accuracy) is associated with greater prefrontal activity (indexed by higher BOLD signal change). This might concurrently produce stronger encoding that results in better subsequent recognition (see Otten et al., 2001). The stronger encoding is not merely a function of encoding time since judgments that were matched for response time still showed greater BOLD signal change for low-frequency words than for high-frequency words. The stronger encoding may be a result of selection and implementation of processes in the frontal lobes that organize input into the medial temporal region (Buckner et al., 1999). The latter structures then integrate or bind these inputs into lasting memories (Moscovitch, 1994) such that repeated encounters could render the recognition and processing of knowledge related to (initially) low-frequency words in the prefrontal cortex less effortful.

It is important to note that our findings relate to recognition and not free recall (the latter being difficult to implement using fMRI). High-frequency words have been shown to be associated with better recall performance when high- and low-frequency words were presented in separate lists (Watkins et al., 2000). However, when low- and high-frequency words in a mixed list were presented for the same amount of time, and when a distractor task was introduced to prevent poststimulus processing, low-frequency words were better recalled (Gregg et al., 1980).

The present work focuses on the left prefrontal region where both word frequency and subsequent memory effects overlap. Although we found additional regions involved in word frequency but not subsequent memory (i.e., left inferior temporal, anterior cingulate, and right prefrontal regions), the recruitment of these regions was not observed in a prior study that also found a word frequency effect (Chee et al., 2002). It is possible that the greater power available in the present study ($n = 16$ vs $n = 8$) or some task-specific differences (Chee et al. (2002) used a different semantic judgment task and a perceptual control task that required nonverbal judgment) accounted for the variance in results. In addition to the left prefrontal region that shows the most robust frequency effect (Fiez et al., 1999; Chee et al., 2002; Fiebach et al., 2002; Kuo et al., 2003), other imaging studies have shown that the word frequency effect may involve the anterior insula, thalamus, and caudate nucleus (Fiebach et

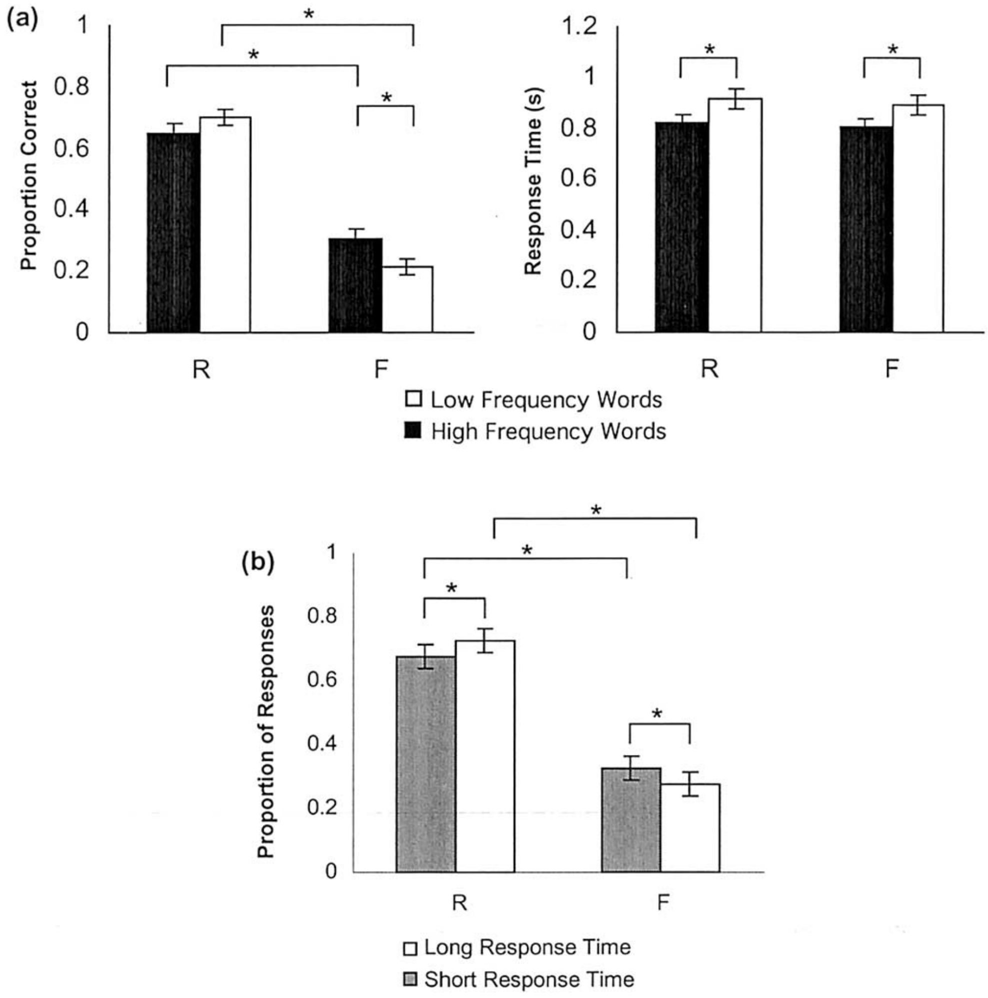

Fig. 4. (a) Proportion of correct responses and response times for living/nonliving judgments ($n = 15$) sorted by subsequent recognition performance. (b) Proportion of responses with long and short response times at encoding that were subsequently remembered of forgotten. R, remembered; F, forgotten, * denotes significance at $P < 0.05$.

al., 2002) as well as the supplementary motor area, left superior parietal cortex, left posterior inferior temporal, left insula, and lingual gyrus (Kuo et al., 2003). With the subsequent memory effect, the most reliably implicated region is again the left prefrontal region. The parahippocampal gyrus (Wagner et al., 1998; Kirchhoff et al., 2000), hippocampus (Wagner et al., 1998; Kirchhoff et al., 2000; Davachi et al., 2001; Otten et al., 2001), and the medial frontal region (Wagner et al., 1998; Kirchhoff et al., 2000; Davachi et al., 2001; Otten et al., 2001, 2002) have been less consistently activated. Thus, while it is tempting to suggest that differences in the functional anatomy are related to word frequency and subsequent memory, we prefer to be cautious about making such a claim with the present data.

Of relevance to the original motivation of this study, which was to uncover how less familiar words become more efficiently processed over time, we postulate that the attainment of greater language proficiency may result in a change in the frequency rank-order of newly learned words in an individual's lexicon. Repeatedly encountering such low-frequency words might reduce the effort required to access information about these words. This might lead to a reduction in the BOLD signal in response to repeated (now more familiar) "low-frequency" words. Over time, these low-frequency words might then produce BOLD signal change that is of comparable magnitude to that elicited by high-frequency words. The plausibility of a reduction in BOLD signal following greater exposure to a set of words is suggested by an earlier cross-sectional study of bilinguals with contrasting language proficiencies in English and Mandarin (Chee et al., 2001). However, a longitudinal study would be necessary to confirm the proposed "learning mechanism."

Attainment of language proficiency, even in the restricted sense of vocabulary building, requires exposure to words in varied contexts. As such, word "proficiency" may be thought of as a consequence of the integration of multiple exposures to that word (Monsell, 1991). Some of these episodes may contribute more and some less to an individual's repository of knowledge about that word. In this regard, the separation of printed word frequency and subse-

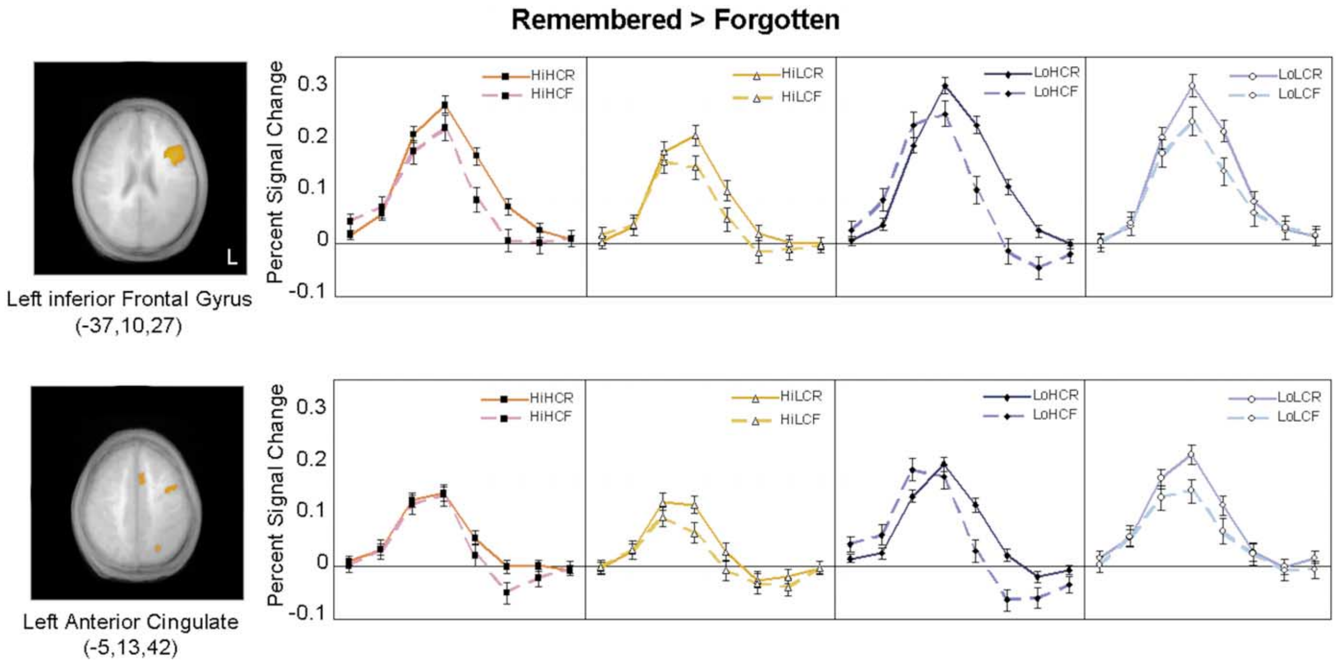

Fig. 5. Axial slices displaying brain regions showing the subsequent memory effect. Talairach coordinates indicate activation peaks for each ROI. BOLD signal plots alongside each axial slice show the relative contribution of each condition within the displayed ROI. Hi, high-frequency words; Lo, low-frequency words; HC, high confidence; LC, low confidence; R, remembered; F, forgotten.

quent memory effects in this study suggests that while low-frequency words may be better remembered, additional processes during encoding may also influence subsequent memory. The nature and relative contribution of such additional processes remain to be uncovered in subsequent studies.

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