NeuroImage **17,** 842–850 (2002)
doi:10.1006/nimg.2002.1244

Reading Anomalous Sentences: An Event-Related fMRI Study of Semantic Processing

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Received March 5, 2001

We report a random-effects analysis of an event-related fMRI study (*n* = 28) of cerebral activity during the reading of sentences that ended with a word that was either congruent or incongruent with the previous sentence context. Event-related potential studies have shown that this task elicits a late negativity peaking around 400 ms poststimulus (N400) that is larger for incongruent than for congruent sentence endings. A direct comparison of the activation for incongruent words versus that for congruent words revealed significantly greater activation for incongruent words than congruent words in bilateral inferior frontal and inferio-medial temporal cortex, left lateral frontal cortex, left posterior fusiform gyrus, bilateral motor cortex, and supplementary motor area. These results are consistent with data from intracranial electrical recording studies of the N400 electrical potential. The results are discussed as they relate to the localization of the cerebral sites underlying semantic processing in general and the localization of the scalp recorded N400 event-related potential in particular. © 2002 Elsevier Science (USA)

Key Words: **semantic processing; sentence processing; event-related fMRI; fMRI; N400.**

INTRODUCTION

For many years investigators have employed noninvasive measures of brain electrical activity to examine the temporal sequence and neural organization of language processing. This research has shown that several components of the event-related potential (ERP) are sensitive to linguistic processes. One component, the N400, a negative deflection in the ERP peaking at approximately 400 ms, can be elicited by words presented in the absence of an appropriate sentence context (Kutas and Hillyard, 1980, 1982, 1983). The N400 is thought to reflect neural activity associated with processes related to semantic or lexical access of word representations (Kutas and Van Petten, 1994) or, alternatively, to processes integrating word representations with current context (Holcomb, 1993). Subsequent research has demonstrated that N400-like potentials are also elicited by nonverbal stimuli, such as faces and pictures (Barrett and Rugg, 1989, 1990). These latter findings raise the possibility that the N400 may reflect more general semantic processes. Interestingly, the N400 elicited by both semantically congruent and semantically incongruent sentence endings has been shown to be abnormal under a number of clinical conditions (e.g., schizophrenia), suggesting that it may index the aberrant neural activity characteristic of impaired thought processes (Niznikiewicz *et al.*, 1997).

Much is now known about the psychological processes mediating the elicitation of the N400. However, relatively little is known regarding the neural sources underlying its generation. Currently, the best data available on the neural generators of the N400 comes from invasive intracranial electrical field potential recordings from epilepsy patients undergoing presurgical assessment (Elger *et al.*, 1997; Guillem *et al.*, 1995; McCarthy *et al.*, 1995; Smith *et al.*, 1986). These studies have demonstrated that negative field potentials in the 300- to 500-ms window are generated in a variety of cerebral sites. Using word-recognition memory tasks, Smith *et al.* (1986) recorded stimulus-locked potentials in the medial temporal lobe, Elger *et al.* (1997) observed such potentials in both medial and lateral temporal lobe, and Guillem *et al.* (1995) recorded large-amplitude, polarity-inverted stimulus-locked potentials from various temporal, frontal, and parietal structures. In a study employing intracranial electrodes to record event-related field potentials during the processing of both congruent and incongruent sentence endings, McCarthy *et al.* (1995) found that the anomalous sentence-ending words elicited a large negative field potential with a peak latency near 400 ms, distributed bilaterally in the anterior medial temporal lobe near the amygdala. Subdural electrodes positioned near the collateral sulcus just inferior and lateral to the amygdala recorded a positive field potential at the same latency.

1053-8119/02 $35.00

The local reversal of the field potential suggests that it was generated in the neocortex near the collateral sulcus and anterior fusiform gyrus.

In summary, studies of intracranial recordings of field potentials elicited by words presented during word recognition memory tasks, or by incongruent sentence endings are consistent in demonstrating stimulus-locked electrical potentials in the vicinity of 400 ms poststimulus in the antero-medial temporal lobe. There is less consistent evidence indicating that such potentials arise in lateral temporal cortex, frontal cortex and parietal cortex. Magnetoencephalography (MEG) studies also suggest temporal lobe sites are involved in the generation of the N400 (Simos *et al.*, 1997).

While these studies have demonstrated that a number of areas are active in the generation of the N400, intracranial studies are limited in a number of important respects. First, the positioning and number of electrodes employed in intracranial studies is usually dictated by clinical symptomatology and second, the patients under study are usually suffering from intractable epilepsy, the cause and course of which may have led to abnormal neurodevelopment. MEG data is limited in its localization power. These issues raise the possibility that brain areas other than those previously reported may be activated during processing of congruent and incongruent terminal words and that these areas may be contributors to the scalp recorded N400.

Previously it has not been possible to evaluate the neural sources of the N400 using standard functional imaging protocols (e.g., PET; block-design fMRI) because these techniques assess cerebral activity averaged over a period of 20 s or more. However, recent developments in functional magnetic resonance (fMRI) imaging have shown that it is possible to measure the hemodynamic response arising from individual brief events (D'Esposito *et al.*, 1999). This technique has been termed event-related fMRI (erfMRI) and has opened up new avenues of experimental protocols for hemodynamic imaging (Josephs *et al.*, 1997; Rosen *et al.*, 1998). For example, several groups of investigators have performed erfMRI studies of cerebral activity associated with processing low probability task-relevant stimuli (Clark *et al.*, 2000; Kiehl *et al.*, 2001a; Kirino *et al.*, 2000; McCarthy *et al.*, 1997; Menon *et al.*, 1997).

Event-related fMRI has a number of limitations, especially that the time course of the hemodynamic response is relatively slow (e.g., 6 s) compared to electrical and magnetic recordings. Nonetheless, there is growing evidence that the sites of activation detected with fMRI are consistent with the sites estimated by modeling the sources of ERP components (Menon *et al.*, 1997). The purpose of the present study was to use event-related fMRI techniques to compare cerebral activity during processing of incongruent sentence endings with that during processing of congruent sentence endings. On the basis of the consistent evidence from intracranial recordings indicating sources for the N400 in anteromedial temporal lobe (Elger *et al.*, 1997; Guillem *et al.*, 1995; McCarthy *et al.*, 1995; Smith *et al.*, 1986), we predicted that processing of incongruent terminal words of sentences would elicit increased hemodynamic activity, relative to that elicited by congruent terminal words, in anterior temporal cortex bilaterally. In light of the evidence from several of these studies of sources in lateral frontal cortex, lateral temporal cortex and parietal cortex, we also anticipated increased hemodynamic activity in at least some of these areas. We employed an MR pulse sequence that allowed us to acquire the entire brain (axial extent, 145 mm) and an experimental methodology that has proven to reliably elicit activation in other event-related fMRI paradigms (Kiehl *et al.*, 2000, 2001a). We collected a large sample size ($n = 28$) to ensure adequate power for a random-effects analysis.

METHODS

Participants. Twenty-eight healthy volunteers (14 men and 14 women; mean age, 25.4 years; standard deviation, 9.68) participated in the study. All participants spoke English as a first language and were right-handed. Participants provided written informed consent and were screened for MRI compatibility before entry into the scanning room. All experimental procedures met with university and hospital ethical approval.

Procedure. The stimuli were composed of 60 sentences presented one word at a time (550 ms duration; 450 ms interstimulus interval (ISI)) to the participant by a computer controlled projection system that delivered a visual stimulus to a rear-projection screen located at the entrance to the magnet bore. The participant viewed this screen through a mirror system attached to the top of the head coil. The scanning room and magnet bore were darkened to allow easy visualization of the experimental stimuli. Half of the sentences (4–10 words in length) ended with a word that was semantically congruent with the context established by the previous part of the sentence (e.g., The dog caught the ball in his MOUTH) and half of the sentences ended with a semantically incongruent terminal word (e.g., They called the police to stop the SOUP). The mean cloze probability was 0.75 and 0.02 for the congruent and incongruent terminal words, respectively. The ISI between sentences was between 2500 and 4500 ms. The participant was cued to the onset of a new sentence by the brief presentation of an asterisk (220 ms duration; 780 ms ISI). All word stimuli, except for the terminal words, were presented in lower case. Terminal words were presented in upper case letters in order to cue the participant to make a sense/no-sense discrimination. Participants used their right index finger to indicate if the sentence made sense and used their right middle finger to indicate if the sentence did not make sense. A commercially available MRI compatible fiber-optic response device (Lightwave Medical, Vancouver, BC, Canada) was used to acquire behavioral responses. Reaction time and accuracy data were computed for both types of sentences. Prior to entry into the scanning room, each participant performed a practice block of six sentences to ensure understanding of the instructions.

Imaging parameters. The imaging protocol was similar to that employed in our previous erfMRI studies (Kiehl *et al.*, 2000, 2001a,b). Imaging was implemented on a standard clinical GE 1.5-T whole-body system fitted with a Horizon Echo-speed upgrade. The participant's head was firmly secured using a custom head holder. Conventional spin-echo T_1 weighted sagittal localizing images were acquired to view the positioning of the participant's head in the scanner and to graphically prescribe the functional image volumes. Functional image volumes were collected with a gradient-echo sequence (TR/TE 3000/40 ms, flip angle 90°, FOV 24 × 24 cm, 64 × 64 matrix, 62.5 kHz bandwidth, 3.75 by 3.75 mm in plane resolution, 5 mm slice thickness, 29 slices), effectively covering the entire brain (145 mm axial extent). This sequence is sensitive to blood-oxygen-level-dependent (BOLD) contrast. A total of 220 brain volumes were acquired. To allow T_1 effects to stabilize, the participants did not begin the task until after the first four brain volumes had been acquired. These initial images were not included in any subsequent analyses.

Image processing. Functional images were reconstructed off-line and the image volumes were realigned using the procedure by Friston *et al.* (1996) as implemented in statistical parametric mapping (SPM99; Friston *et al.*, 1995). Translation and rotation corrections did not exceed 2.0 mm and 2.0°, respectively, for any of the participants. A mean functional image volume was constructed for each participant from the realigned image volumes. This mean image volume was then used to determine parameters for spatial normalization into the modified Talairach space employed in SPM99. In this space, coordinates are expressed relative to a rectangular coordinate frame with the origin at the midpoint of the anterior commissure and the *y*-axis passing through the posterior and anterior commisures. The normalization parameters determined for the mean functional volume were then applied to the corresponding functional image volumes for each participant. The normalized functional images were then smoothed with an 8-mm full-width at half-maximum Gaussian filter.

The timing of the stimulus presentation was such that one-third of the terminal words were presented at the beginning of the 3-s image-acquisition period, one-third were collected 1 s into the image-acquisition period, and one-third were collected 2 s into the image-acquisition period. This procedure effectively sampled the hemodynamic response every second (Josephs *et al.*, 1997). Event-related responses to the congruent and incongruent terminal words were then modeled using a synthetic hemodynamic response composed of two gamma functions (see Josephs *et al.* (1997) for the mathematical model and (Friston *et al.* (1998) for an illustration). The first gamma function modeled the hemodynamic response using a peak latency of 6 s. The second gamma function was used to model the small "overshoot" of the hemodynamic response on recovery (Friston *et al.*, 1998a,b; Josephs *et al.*, 1997). We also modeled and removed the variance associated with the respective temporal derivatives of these two gamma functions in order to compensate for slight variations in the peak latency of onset of the hemodynamic response. The advantage of modeling the hemodynamic response in terms of basis functions, in this case, gamma functions and their derivatives, is fourfold. First, it has been shown that these gamma functions provide both reasonable and comprehensive models of the hemodynamic response (Boynton *et al.*, 1996; Friston *et al.*, 1994). Second, by fitting the hemodynamic response for each voxel, we were able to effectively model variations in the hemodynamic response in both amplitude and latency between different brain regions and between different events. Third, the creation of the parameter estimates in terms of peristimulus time allows us to achieve an effective temporal resolution less than the total acquisition time (Josephs *et al.*, 1997). This temporal resolution cannot be achieved using standard averaging techniques (akin to ERP studies). Last, formulating the model in this way allows us to use standard procedures developed for analyzing serially correlated fMRI time series that employ the general linear model. Variations in global signal intensity were removed using proportional scaling. There were no significant differences between the correlation of global signal and congruent and incongruent stimuli (see Aguirre *et al.*, 1998; Desjardins *et al.*, 2001, for more). Low-pass and high-pass frequency filters were applied to remove high-frequency scanner artifacts and low-frequency confounds, respectively.

Contrasts were then specified to create images representing the difference between the amplitude of the fitted response to incongruent terminal words and the amplitude of the fitted response to congruent terminal words for each of the 28 participants. These difference images were then entered into a random-effects one-sample *t* test (27 degrees of freedom) to identify brain regions in which a significantly larger hemodynamic response was associated with incongruent terminal words than for congruent terminal words.

To examine the effect of reaction time difference between incongruent and congruent stimuli, we computed the regression of mean reaction time difference between incongruent and congruent stimuli for each participant on hemodynamic difference between incongruent and congruent stimuli, for each voxel. Using SPM, we tested for voxels in which the regression slope was significant. In addition, in each voxel, we tested for the significance of the intercept, which represents hemodynamic response difference between incongruent and congruent events, adjusted to zero difference in reaction time.

RESULTS

Behavioral data. The analyses of the accuracy data indicated that the task was performed almost perfectly. Participants correctly classified 99.1% (SD 1.4) and 98.35% (SD 1.3) of the congruent and incongruent sentence endings, respectively. Response times for the incongruent terminal words and congruent terminal words were 985 ms (SD 265) and 932 ms (SD 233 ms), respectively ($t(27) = 2.92$, $P < 0.03$).

Imaging data. The random-effects analysis, examining the entire brain, revealed that the amplitude of the hemodynamic responses for incongruent stimuli was greater than the amplitude of the hemodynamic response for congruent stimuli in four significant clusters, embracing left lateral frontal cortex and anterior temporal cortex, bilateral motor cortex, right inferior frontal and anterior temporal cortex, and left posterior fusiform gyrus (see Fig. 1; Table 1).

Comparison of the congruent terminal words with the incongruent terminal words failed to reveal any brain regions in which significantly larger hemodynamic responses were found for congruent terminal words than for incongruent terminal words.

The regression analysis revealed that increasing reaction time difference predicted an increase in hemodynamic difference between incongruent and congruent stimuli in a cluster of 101 voxels in the right parietal cortex (corrected cluster significance, $P = 0.016$; coordinates of peak, 32, −40, −56; peak $z = 3.82$; uncorrected $P < 0.001$). There were also small clusters of suprathreshold voxels, which were not significant after correcting for multiple comparisons, in occipital cortex bilaterally and in the left middle frontal gyrus. Examination of the regression intercept in each voxel demonstrated that after adjusting to a zero difference in reaction time between congruent and incongruent stimuli there were four prominent clusters of suprathreshold voxels in which the hemodynamic response to incongruent events was greater than that to congruent events (Table 2). These four clusters were very similar in location and extent to those revealed in the primary analysis (Table 1). After correcting for multiple comparisons, three of the clusters were significant at the level $P < 0.05$, while the corrected significance for the smallest cluster, located in left fusiform gyrus, was $P = 0.066$. Adjusting to zero difference in reaction time had a negligible effect on the z values at the local maxima within each of the clusters.

DISCUSSION

This study was designed to elucidate the cerebral sites selectively activated by processing of incongruent terminal words of sentences relative to that observed for processing congruent terminal words of sentences. Consistent with the data from intracranial electrode recordings during the processing of incongruent sentence endings (McCarthy *et al.,* 1995), we observed greater activation during processing of incongruent terminal words than with congruent terminal words in anterior temporal cortex bilaterally. In both hemispheres, the region of activation extended from anterior temporal lobe into the adjacent inferior frontal gyrus. This extension was most pronounced on the left, where the site of most significant activation was located in dorsolateral prefrontal cortex.

The left inferior frontal gyrus has been implicated in numerous language-related cognitive operations, including verb generation, stem completion, and concrete/abstract judgments. A number of investigators have interpreted these findings as support for the hypothesis that the left inferior frontal gyrus mediates the retrieval of semantic knowledge (Demb *et al.,* 1995; Fiez, 1997; Kapur *et al.,* 1994; Petersen *et al.,* 1989). Insofar as processing contextually incongruent words might entail a more extensive search for semantic information than the processing of congruent words, the effects observed in the left inferior frontal cortex in the present study are consistent with this hypothesis regarding the function of prefrontal cortex.

There are a number of other hypotheses regarding the function of the left inferior frontal cortex based on evidence from neuroimaging studies. Cohen and Servan-Schreiber (1992) argued that lateral frontal cortex mediates context-sensitive responses, particularly in tasks where a response other than the prepotent one must be selected (i.e., response competition). More recently, Thompson-Schill and colleagues (1997) have argued that the activation of the left inferior frontal gyrus during semantic tasks is the result not of semantic retrieval per se, but of the need to select some relevant feature of semantic knowledge from a set of competing alternatives. In a similar vein, Gabrieli *et al.* (1998), in a review of the functional neuroimaging literature on the function of the left lateral frontal cortex, concluded that this region is primarily involved with domain-specific semantic working memory capacity that is invoked more for semantic than nonsemantic analyses. In particular, they argued that the left inferior frontal gyrus is more strongly activated by tasks in which a response must be selected from among more than a few legitimate alternatives.

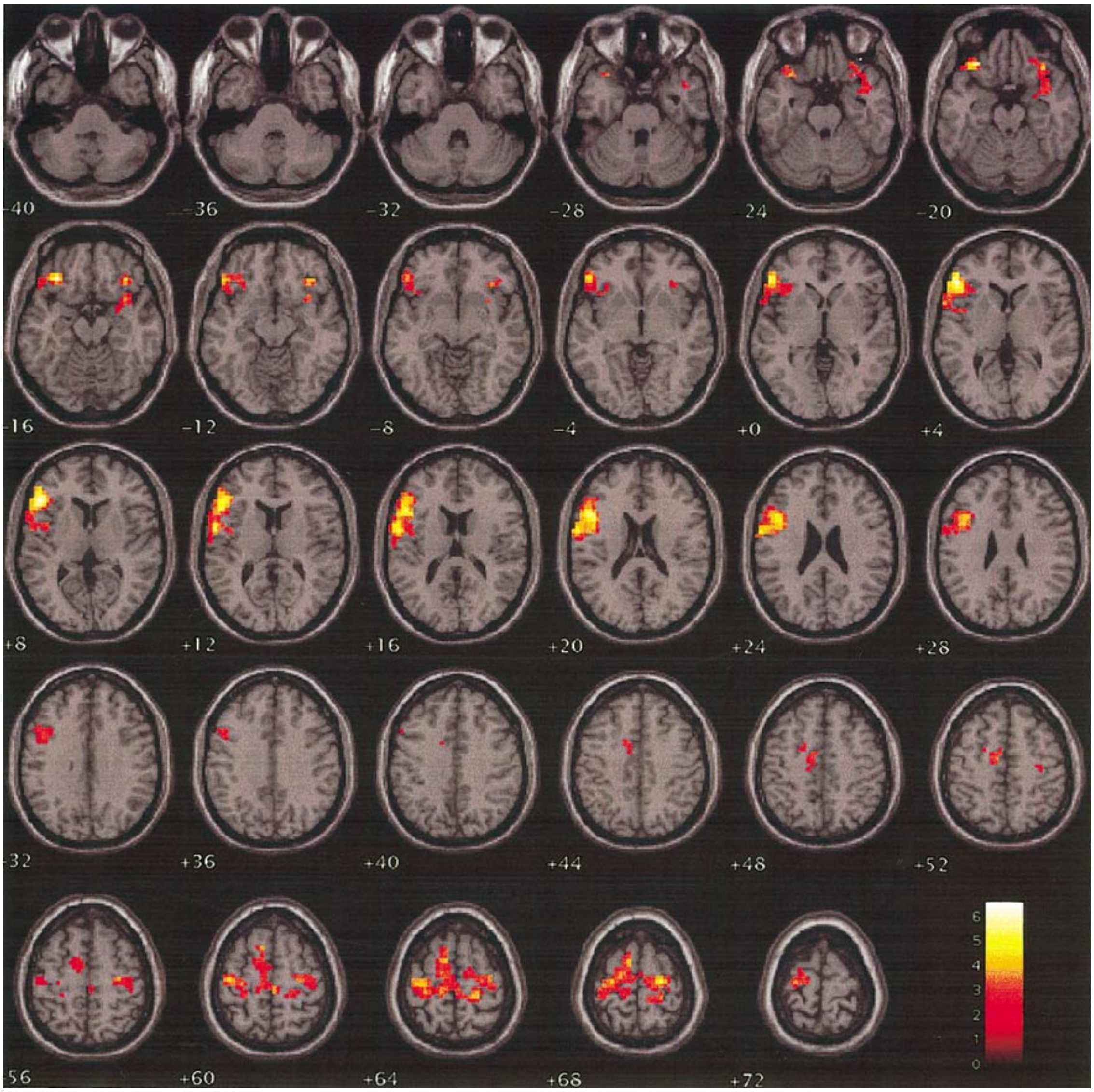

FIG. 1. Illustration of the cerebral sites in which significantly greater hemodynamic activity was observed for processing of incongruent terminal words of sentences compared to congruent terminal words of sentences. Data are presented in the modified Talairach space employed in SPM99 and are rendered onto a standard reference brain. The view is in neurological convention (e.g., left hemisphere is on the left). The *z* levels in Talairach space are listed on each slice with *t*-score color bar located in bottom right corner (see Table 1 and the results section for description of cluster sizes, anatomical labels, and significance values).

Our finding that incongruent terminal words of sentences recruits stronger left lateral frontal cortex activation than congruent terminal words of sentences could be interpreted as support for any of the above theories of dominant prefrontal cortex function. As semantic processing tasks often entail a degree of conflict between competing alternatives, these hypotheses are not mutually exclusive. Determining whether or not semantic processing engages the left lateral frontal cortex more strongly than a nonsemantic task that entails resolution of a similar degree of conflict would require a method for separately quantifying the amount of conflict and the amount of semantic processing. Such a distinction goes beyond the objectives of this study.

The anterior-medial temporal cortex has also been implicated in semantic processing. Vandenberghe *et al.* (1996) observed that both word and picture stimuli elicited semantic related activity in the anterior temporal cortex. In addition to activation in left anterior temporal lobe, Vandenberghe *et al.* found semantic specific activity in left inferior frontal gyrus, left middle temporal gyrus, left posterior fusiform gyrus, cerebellum, and left posterior parietal cortex. Our results partially confirm these findings. However, in the present study, greater activation for incongruent than

TABLE 1

SPM99 Results Output for the Comparison of Incongruent Terminal Words of Sentences versus Congruent Terminal Words of Sentences

Set level		Cluster level			Voxel level				Talairach coordinates			
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_e)	$p_{uncorrected}$	x	y	z	Anatomical label (Region)
0.037	**58**	**0.000**	**438**	**0.000**	**0.016**	**6.60**	**(5.05)**	**0.000**	**−48**	**32**	**4**	**Left lateral frontal and**
					0.025	6.39	(4.95)	0.000	−32	32	−16	**anterior temporal cortex**
					0.124	5.63	(4.54)	0.000	−48	16	20	
		0.030	**66**	**0.001**	**0.307**	**5.16**	**(4.26)**	**0.000**	**−48**	**−52**	**−16**	**Left posterior fusiform gyrus**
					0.915	4.24	(3.68)	0.000	−48	−60	−20	
					1.000	3.49	(3.14)	0.001	−48	−44	−24	
		0.000	**336**	**0.000**	**0.340**	**5.10**	**(4.23)**	**0.000**	**24**	**−16**	**68**	**Bilateral precentral gyrus**
					0.831	4.40	(3.79)	0.000	−40	−16	60	
					0.902	4.26	(3.70)	0.000	−32	−20	64	
		0.012	**79**	**0.000**	**0.741**	**4.53**	**(3.87)**	**0.000**	**36**	**32**	**−16**	**Right anterior temporal**
					0.999	3.72	(3.31)	0.000	36	12	−16	**and lateral frontal cortex**
					1.000	3.39	(3.06)	0.001	28	32	−24	

Note. Four significant clusters emerged from the random effects analyses ($P < 0.01$ threshold for inclusion in the cluster). The three sites of peak activation within each of the four clusters are listed. Cluster-level statistics and the voxel of peak activation are highlighted in bold.

for congruent terminal words was not observed in the cerebellum or left posterior parietal cortex.

Mazoyer *et al.* (1993) report that activation is observed in the bilateral anterior temporal lobes during processing of meaningful stories. Bottini *et al.* (1994) found that comprehension of sentences was associated with activation in left lateral frontal cortex, and the anterior temporal pole, among other areas (Bottini *et al.*, 1994). Bavelier *et al.* (1997) using a block design, found that the anterior temporal lobes were activated during sentence reading, an effect interpreted as support for the notion that these regions are specifically involved during language comprehension in sentence contexts (Bavelier *et al.*, 1997). Our results are consistent with the conclusions of Price (2000), who in a recent review argued that anterior temporal activation seems to reflect the specific requirements of semantic decisions using verbal material (Kircher *et al.*, 2001; St. George *et al.*, 1999). Furthermore, using data from PET studies of reading and listening to nouns of varying imageability, Wise *et al.* (2000) concluded that access to the representations of word meaning is dependent on heteromodal temporal lobe cortex.

The observed results in the present study are also largely consistent with other fMRI studies of anomalous sentence processing. Kuperberg *et al.* (2000), using

TABLE 2

SPM99 Results Output for the Comparison of Incongruent Terminal Words of Sentences versus Congruent Terminal Words of Sentences after Using Linear Regression to Adjust to a Reaction Time Difference of Zero between Incongruent and Congruent Events

Set level		Cluster level			Voxel level				Talairach coordinates			
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_e)	$p_{uncorrected}$	x	y	z	Anatomical label (Region)
0.003	**66**	**0.000**	**461**	**0.000**	0.001	7.81	(5.60)	0.000	−32	32	−16	**Left lateral frontal and**
					0.004	**7.22**	**(5.34)**	**0.000**	**−48**	**32**	**4**	**anterior temporal cortex**
					0.058	6.00	(4.74)	0.000	−48	16	20	
		0.066	**75**	**0.001**	**0.171**	**5.47**	**(4.45)**	**0.000**	**−48**	**−52**	**−16**	**Left posterior fusiform gyrus**
					0.785	4.47	(3.83)	0.000	−52	−52	−8	
					1.000	3.19	(2.91)	0.002	−36	−36	−16	
		0.000	**389**	**0.000**	**0.412**	**4.98**	**(4.16)**	**0.000**	**24**	**−16**	**68**	**Bilateral precentral gyrus**
					0.546	4.79	(4.04)	0.000	−8	16	60	
					0.807	4.44	(3.81)	0.000	−40	−16	60	
		0.025	**93**	**0.001**	**0.583**	**4.75**	**(4.01)**	**0.000**	**36**	**32**	**−16**	**Right anterior temporal and**
					0.999	3.70	(3.30)	0.000	36	12	−16	**lateral frontal cortex**
					1.000	3.49	(3.14)	0.001	28	32	−24	

Note. Cluster-level statistics and the voxel of peak activation from the primary analysis (shown in Table 1) are highlighted in bold ($P < 0.01$ threshold for inclusion in the cluster).

a blocked design fMRI study, observed activation associated with processing of auditory semantically anomalous sentences, relative to normal sentences, in left anterior temporal lobe, left insula, and left posterior temporal lobe. They also observed similar effects in right posterior temporal lobe, bilateral cerebellum, and right striatum and cuneus. Ni *et al.* (2000), using spoken sentences, observed that processing of semantically anomalous sentences, relative to a tone discrimination baseline, was associated with activation in bilateral inferior frontal gyrus, posterior superior temporal gyrus, and medial frontal gyrus. These latter results are largely consistent with those observed in the present experiment. However, Ni *et al.* did not examine cortical areas inferior to the intercommissural plane, making it unclear whether inferior regions may have been involved in their study of spoken sentences.

Activity in bilateral motor cortex was also observed to differentiate incongruent from congruent terminal words of sentences. There are a number of possible reasons why bilateral motor cortex was more strongly recruited for processing incongruent terminal words of sentences than congruent terminal words of sentences. First, the task required that participants respond to incongruent words with their middle finger on the left hand and respond to congruent terminal words with their left index finger. Furthermore, it is also possible that response preparation time was longer for incongruent stimuli, leading to greater activation of motor cortex. Thus, it is plausible that the differences observed in motor cortex for the comparison of incongruent terminal words versus congruent terminal words is due, at least in part, to the different motor requirements of the task. However, the fact that the difference was observed bilaterally, while responses were all performed using the left hand, makes it unlikely that this is the principal factor accounting for differences in activation of motor cortex. Second, processing incongruent terminal words of sentences might involve more covert speech processing (possibly including mouth and tongue motor systems) than congruent terminal words of sentences. That is, participants may have engaged in strategies that involved subvocalization. The fact that the observed motor activation was present in bilateral cortex is consistent with this interpretation, although the location of the peak activation was superior to the usual representation of the tongue and pharynx in motor cortex.

The reaction time data reveal that the participants took, on average, approximately 5% longer, to respond to the incongruent stimuli than to the congruent stimuli. Under circumstances where speed of response is emphasized, response time is conventionally taken to be a measure of the amount of processing required. We elected not to place emphasis on response speed so as to minimize the likelihood that response time itself would be a major determinant of the observed pattern of brain activity. Nonetheless, the data indicate that increased demand on some aspects of processing during incongruent trials was associated with an increase in time devoted to those aspects of processing. The results of the regression against reaction time difference indicate that that increasing reaction time difference was significantly associated with increasing difference in hemodynamic response to incongruent and congruent stimuli in the right parietal cortex. However, in the four prominent regions where the hemodynamic response was greater for incongruent stimuli than for congruent stimuli, adjusting to a zero difference in reaction time produced only a trivial change in the z values for the most significant voxels.

In conclusion, we have shown that in comparison with the processing of congruent terminal words, the processing of incongruent terminal words is associated with greater activation in the left inferior frontal gyrus, bilateral anterior temporal lobe, and left posterior fusiform gyrus. Because of the relatively poor temporal resolution of fMRI, it is not possible to determine directly whether or not electrical activity at the sites of activation observed in this study contribute to the N400 ERP component. However, the observed activation in the anterior temporal lobe, bilaterally, is consistent with the evidence from intracranial recording, indicating bilateral anterior temporal lobe sources for the N400 electrical component (Elger *et al.*, 1997; Guillem *et al.*, 1995; McCarthy *et al.*, 1995; Smith *et al.*, 1986). The issue of whether or not the other areas of activation during the processing of incongruent sentence endings observed in this study contribute to the N400 remains uncertain. However, the fact that Guillem *et al.* (1995) observed large-amplitude, polarity-inverted event-related electrical potentials around 400 ms after stimulus presentation during a word recognition memory task at widely distributed sites including lateral frontal cortex suggests that the frontal activity observed in our study might also contribute to the N400 electrical component.

ACKNOWLEDGMENTS

We thank Alex MacKay, Ken Whittall, Bruce Forster, Andra Smith, Adrianna Mendrek, and Timothy Duty for their assistance. We also thank MR technicians Trudy Shaw, Karen Smith, and Silvia Renneberg. This research was supported in part by grants from the Dr. Norma Calder Foundation, Medical Research Council (MRC) of Canada, and funds from the Schizophrenia Division, Department of Psychiatry, University of British Columbia. The first author was supported by the Michael Smith Graduate Scholarship, Medical Research Council of Canada. The data presented in this article were collected while the authors were at the University of British Columbia.

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