Neural Pathways Involved in the Processing of Concrete and Abstract Words

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Abstract: The purpose of this study was to delineate the neural pathways involved in processing concrete and abstract words using functional magnetic resonance imaging (fMRI). Word and pseudoword stimuli were presented visually, one at a time, and the participant was required to make a lexical decision. Lexical decision epochs alternated with a resting baseline. In each lexical decision epoch, the stimuli were either concrete words and pseudowords, or abstract words and pseudowords. Behavioral data indicated that, as with previous research, concrete word stimuli were processed more efficiently than abstract word stimuli. Analysis of the fMRI data indicated that processing of word stimuli, compared to the baseline condition, was associated with neural activation in the bilateral fusiform gyrus, anterior cingulate, left middle temporal gyrus, right posterior superior temporal gyrus, and left and right inferior frontal gyrus. A direct comparison between the abstract and concrete stimuli epochs yielded a significant area of activation in the right anterior temporal cortex. The results are consistent with recent positron emission tomography work showing right hemisphere activation during processing of abstract representations of language. The results are interpreted as support for a right hemisphere neural pathway in the processing of abstract word representations. *Hum. Brain Mapping 7:225–233, 1999.* © 1999 Wiley-Liss, Inc.

Key words: lexical decision, abstract words; concrete words, fMRI

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INTRODUCTION

Considerable controversy exists regarding the cognitive operations and neural pathways involved in processing concrete and abstract language. Early research on verbal learning and memory suggested that the cognitive operations (e.g., lexical and memory access) involved in processing concrete words differ from those operations involved in processing abstract words [e.g., Paivio, 1971, 1978]. In lexical decision tasks, healthy participants respond faster and more accurately to concrete words than to abstract words [Day, 1977; James, 1975; Kroll and Merves, 1986]. This pattern of results has been interpreted in terms of a "dual-code" theory of language representation [Paivio, 1971, 1978, 1991]. According to this theory, abstract words are coded in memory in a verbal representation only, while concrete words are coded both verbally and imaginatively. In this hypothetical model, the

verbal stream is located in the left hemisphere and the image-based stream is located in the right hemisphere. Dual-code theorists argue that lexical access to concrete words is faster and more accurate than lexical access to abstract words, because concrete words are processed by two concurrent processing streams, rather than a single processing stream.

Early neuropsychological data were interpreted as support for a dual-code interpretation of concrete/abstract processing differences. For example, some brain-damaged patients appear to show selective deficits in one or the other class of words [Coltheart, 1987; Warrington, 1981]. These putatively left hemisphere brain-damaged patients show a differential availability of concrete words over abstract words. This finding led to the notion that there is a right hemisphere lexicon which provides access to some concrete words [see also Chiarello et al., 1987; Kounios and Holcomb, 1994].

The notion of a right hemisphere lexicon for concrete words is at odds, however, with a number of other lines of research. In a seminal series of positron emission tomography (PET) studies, Petersen et al. [1988, 1989, 1990] demonstrated that concrete words are processed primarily by left hemisphere language regions. Specifically, these PET studies localized the neural processes involved in reading concrete word stimuli to the left inferior frontal lobe region. More recent PET work indicated that the left posterior inferior temporal region and adjacent fusiform gyrus are activated during reading concrete nouns [Bookheimer et al., 1995; Damasio et al., 1996]. In addition, neuropsychological research has firmly established that the left hemisphere temporal lobe areas are involved in processing concrete words [Damasio et al., 1996]. Damasio et al. [1996] showed that patients with specific lesions of the left temporal lobes often display selective deficits in processing different categories of concrete words (e.g., tools, animals). These studies noted the lack of right hemisphere activation during the processing of concrete nouns.

In a lexical-decision PET study that did not attempt to distinguish between concrete and abstract words, Rumsey et al. [1997] found that processing words was associated with activation at a set of left-sided sites including the fusiform, inferior parietal, middle temporal, and inferior frontal gyri. They also observed activation in the posterior fusiform gyrus on the right, but it is probable that this posterior site was engaged in lower-level sensory processing. In another study that did not distinguish between concrete and abstract words, Price et al. [1994] found that the right middle temporal gyrus was activated during the performance of a lexical decision task when the stimuli were presented for a brief period (e.g., 150 msec).

Interestingly, other PET work suggests that the right hemisphere may play an interpretative role in processing abstract language [Beauregard et al., 1997; Bottini et al., 1994]. Bottini et al. [1994] found that several areas in the right hemisphere, including the prefrontal cortex and middle temporal gyrus, were activated during comprehension of metaphors. In a similar vein, a number of studies have shown that right hemisphere brain-damaged patients show deficits in the comprehension and production of the connotative meanings of words and figures of speech [Gardner and Denes, 1973; Winner and Gardner, 1977]. Patients with right hemisphere brain damage also show deficits in verbal reasoning ability [Caramazza et al., 1976], interpretation of verbal humor [Brownell et al., 1983], and in understanding prosody of speech [Ross, 1981]. Beeman et al. [1994] argued that the linguistic strength of the right hemisphere is its ability to bring together connotative associations, while the left hemisphere is primarily involved in processing the denotative representations of language. More recently, Beauregard et al. [1997], using PET, compared passive viewing of abstract words with a plus-sign baseline condition and showed that there was a significant area of activation in the right inferior frontal gyrus. It is important to note that this right hemisphere activation was found for abstract word processing but not for concrete words minus baseline comparisons, or for emotional words minus baseline comparisons [Beauregard et al., 1997; see also D'Esposito et al., 1997].

Thus, converging evidence suggests that the left hemisphere primarily is involved in processing concrete language, while the right hemisphere may play a special role in the interpretation of abstract representations of language. Based on these assumptions, we hypothesized that lexical access to concrete words would primarily activate left hemisphere language areas and that lexical access to abstract words would involve a coordinated effort of both the left and right hemisphere language areas. That is to say, we predict greater right hemisphere activation will be found when comparing the processing of abstract words with the processing of concrete words.

In the present experiment we used functional magnetic resonance imaging (fMRI) to explore the neural pathways involved in processing concrete and abstract language while participants performed a series of lexical decision blocks (i.e., Is it a word or not?) alternating with a baseline condition. The lexical decision blocks were composed of concrete words and pseudowords or abstract words and pseudowords.

This paradigm allowed us to directly contrast the neural pathways involved in processing abstract linguistic stimuli with those involved in processing concrete linguistic stimuli.

METHODS

Participants

Six right-handed healthy male volunteers aged 22–26 years (mean, 24.5), all of whom spoke English as a first language and were not bilingual, volunteered for the experiment. All participants gave written informed consent after the experimental methodology was explained and volunteers were screened for magnetic resonance (MR) compatibility prior to entry into the scanning room.

Materials

Stimulus words (3–8 letters in length) were selected from the word norms of Toglia and Battig [1978] and were either concrete or abstract. Words rated as more than .75 standard deviations above or below the mean concreteness rating contained in the word norms were defined as concrete and abstract, respectively. The word lists for each task did not differ in word frequency or length [Francis and Kucera, 1982]. Furthermore, only affectively neutral words (at or within one standard deviation of the mean pleasantness rating given in Toglia and Battig [1978]) were selected in order to eliminate any confound of emotionality. We developed sets of pronounceable pseudowords by selectively altering one letter of each of the concrete and abstract words.

Procedure

Imaging was implemented on a standard clinical GE 1.5 T whole body MRI (General Electric, Milwaukee, WI) system fitted with a Horizon echo-speed upgrade (General Electric, Milwaukee, WI). The participant's head was firmly secured using a custom head holder, and external references were used to position the anterior commissure-posterior commissure (AC-PC) line at right angles to the slice-select gradient. Conventional spin echo T_1-weighted sagittal localizers were acquired to confirm external landmarking and prescribe a subsequent 3D SPGR (TR/TE 11.2/21 msec, flip angle 60, FOV 26 × 26 cm, 256 × 256 matrix, slice thickness 1.5 mm) volume acquisition. Functional image volumes were collected with a gradient-echo sequence (TR/TE 2,500/50 msec, flip angle 90, FOV 24 × 24 cm, 64 × 64 matrix, 62.5 kHz bandwidth, 3.75 × 3.75mm in plane resolution, 4 mm slice thickness, 23 slices).

Two stimulus runs were presented, each consisting of a series of four 30-sec lexical decision blocks alternating with a baseline session. Prior to each run, images were collected during a 10 second rest session, to allow for T1 effects to stabilise. These images were not included in any subsequent analyses. During the lexical decision blocks, 15 letter stimuli (350 msec duration; 1,650 msec interstimulus interval) were randomly presented. All stimuli were presented in capital letters. During the baseline session, the characters "*****" were continuously displayed for 29.5 sec (500 msec interstimulus interval). Stimulus runs were balanced such that equal proportions of word and pseudoword stimuli were presented. Lexical decision blocks consisted of either concrete words and associated pseudowords or abstract words and associated pseudowords. The word and its associated pseudoword did not appear during the same run. Concrete and abstract lexical decision blocks were presented in random order. The participant was unaware of the concrete/abstract manipulation. Participants were instructed to respond with one hand each time the letter stimulus presented formed a real English speaking word and to respond with their other hand if the letter stimulus was not an English speaking word. Reaction time and accuracy were equally stressed. A commercially available MRI-compatible fiber-optic response device (Lightwave Medical, Vancouver, British Columbia, Canada) was used to acquire behavioral responses. The hand used to make the response was counterbalanced across participants. Prior to entry into the scanning room, each participant performed a practice block of lexical decisions, repeated twice, to insure he understood the instructions. None of the stimuli used in the practice blocks were used in the fMRI session.

Stimuli were presented 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.

Reaction times were computed on trials for which the participant responded correctly within 1,500 msec poststimulus. Errors included incorrect responses within 1,500 msec poststimulus or any response with a latency of greater than 1,500 msec following onset of target stimulus. We performed repeated-measures Word (concrete × abstract) × Lexical (real word × pseudoword) analyses of variance (ANOVAs) on the reaction time and accuracy data.

Image processing

Functional images were reconstructed offline on a computer workstation. The two runs were separately realigned and motion-corrected using the procedure of Friston et al. [1995; see also Worsley and Friston, 1995], as implemented in Statistical Parametric Mapping (SPM96, Wellcome Institute of Cognitive Neurology, London, England). Translation and rotation corrections did not exceed 1.5 mm and 1.5°, respectively, for any of the participants. A mean functional image volume was constructed for each participant for each run from the realigned image volumes. This mean image volume was then coregistered to the participant's structural MRI volume [Ashburner and Friston, 1997]. The coregistration results indicated minimal movement between the structural MRI and functional MRI scans. The structural MRI volume was used to determine parameters for spatial transformation into the modified Talairach space employed in SPM96. 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 commissures. Anatomical locations corresponding to specific coordinates were reported as specified in the University of Texas Talairach Daemon [Lancaster et al., 1998]. The normalization parameters 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. Variations in global signal intensity were removed using proportional scaling. Time series were analyzed by determining correlations between the observed time course in each voxel and a temporally smoothed (2.8 sec) delayed boxcar (6 sec) waveform. A correction for multiple comparisons based on the theory of Gaussian fields (SPM96) was employed. Four comparisons were examined: 1) concrete stimuli vs. baseline; 2) abstract stimuli vs. baseline; 3) abstract stimuli vs. concrete stimuli; and 4) concrete stimuli vs. abstract stimuli. In addition, areas of deactivation during word stimuli relative to baseline were identified by comparing baseline with concrete stimuli and with abstract stimuli.

RESULTS

Behavioral data

Responses to concrete stimuli (words and pseudo-words) were more accurate than to abstract stimuli
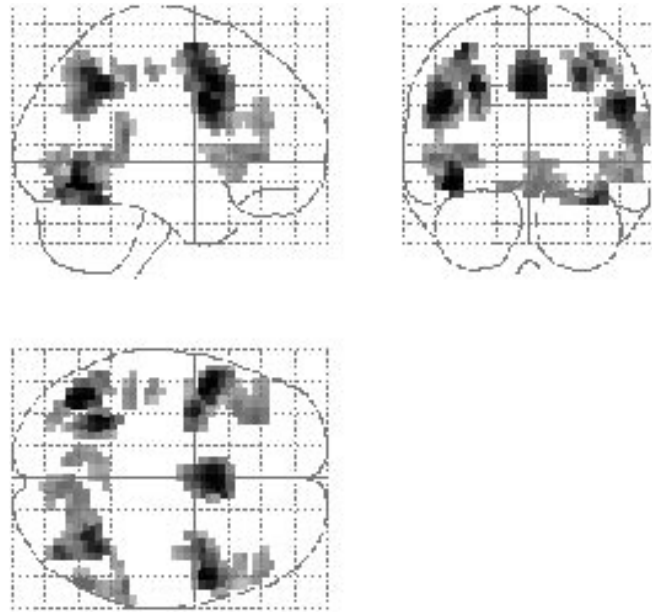

Figure 1.
Statistical parametric map of areas of significant activation during the processing of concrete stimuli relative to baseline. The voxels in which there is a significant increase in signal (p < 0.001) during processing of concrete stimuli are projected onto axial (lower left), sagittal (upper left) and coronal (upper right) planes. The shade of gray at a particular location represents the significance of the most significant voxel on the line projecting to that location (see Tables for z-scores).

(main effect of Word, F (1,5) = 10.00, $P < .025$). Responses to concrete words (M = 581 msec; SD = 65.3) and abstract words (M = 627 msec; SD = 89.9) were faster than responses to pseudoconcrete (M = 700 msec; SD = 93.5) and pseudoabstract (M = 681 msec; SD = 92.4) stimuli (main effect of Lexical, F (1,5) = 9.06, $P < .03$). Five out of 6 participants responded faster to concrete words than to abstract words. However, this difference in response speed did not reach statistical significance ($P < .08$).

Image data

Statistical parametric maps for concrete stimuli vs. baseline and abstract stimuli vs. baseline comparisons are illustrated in Figures 1 and 2, respectively. Significant areas of activation for these comparisons are summarized in Tables I and II, respectively. Comparisons of concrete stimuli vs. baseline showed significant activation in the bilateral superior parietal lobules, anterior cingulate, left inferior frontal gyrus, precuneus, bilateral fusiform gyrus, left middle temporal

gyrus, and right posterior superior temporal gyrus. In addition, significant activation was found in the bilateral premotor cortex, consistent with the fact that the lexical decision was indicated with a button press. Comparison of abstract stimuli vs. baseline revealed a very similar pattern of activation, as did the concrete stimuli vs. baseline comparison (see Table II), though there was evidence of greater right temporal and frontal activation in the abstract stimuli vs. baseline comparison than the concrete stimuli vs. baseline comparison. This observation was confirmed by the presence of a significant area of activation in the right superior temporal gyrus for the direct comparison of abstract stimuli vs. concrete stimuli (see Table III). Activation was also observed for this comparison in the right inferior frontal gyrus (x, y, z = 52, 26, 20); however, this activation did not reach conventional levels of statistical significance after correction for multiple comparisons (z-score = 4.28, P < .0001, uncorrected). There were no significant areas of activation for the concrete stimuli vs. abstract stimuli comparison.

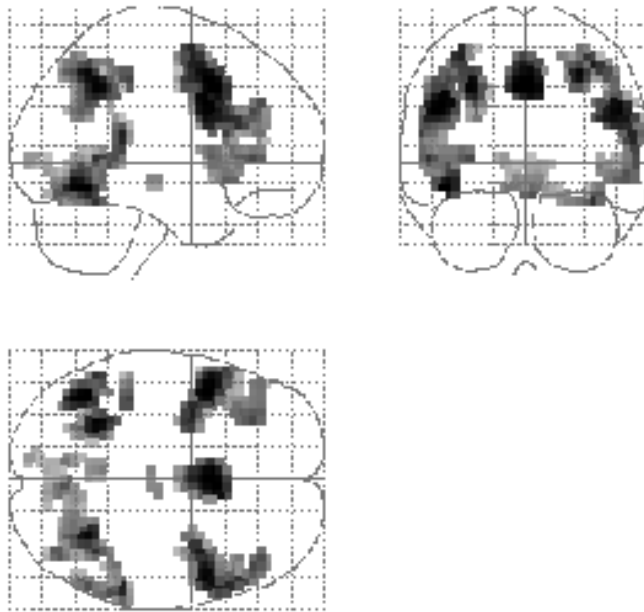Significant areas of deactivation (e.g., greater activation during baseline than lexical decision blocks) were

Figure 2.

Statistical parametric map of areas of significant activation during the processing of abstract stimuli relative to baseline. The voxels in which there is a significant increase in signal (p < 0.001) during processing of abstract stimuli are projected onto axial (lower left), sagittal (upper left) and coronal (upper right) planes. The shade of gray at a particular location represents the significance of the most significant voxel on the line projecting to that location (see Tables for z-scores).

TABLE I. Significant areas of activation and deactivation for the concrete stimuli vs. baseline comparisons

Region	Talairach coordinates (mm) x	y	z	Z-score value
Activations				
1. L fusiform gyrus	−41	−60	−12	7.97***
2. L inferior frontal gyrus	−49	8	32	7.68***
3. R inferior frontal gyrus	52	4	32	7.68***
4. Cingulate gyrus	0	11	40	7.65***
5. L inferior parietal lobule	−30	−52	40	7.58***
6. R cerebellum	38	−52	−20	7.21***
7. L middle frontal gyrus	−34	0	60	7.10***
8. R superior parietal lobule	30	−60	48	7.00***
9. R middle frontal gyrus	38	4	52	6.91***
10. R cerebellum	41	−71	−16	6.59***
11. R fusiform gyrus	40	−74	−12	5.92***
12. L inferior frontal gyrus	−30	0	44	5.80***
13. R superior temporal gyrus	56	−38	16	5.47**
14. L middle temoral gyrus	−52	−52	4	5.46**
15. L insula	−30	34	4	5.36**
16. R cerebellum	4	−71	−12	5.11**
17. L insula	−34	22	8	4.81*
18. L inferior parietal lobule	−45	−34	48	4.55*
19. L cerebellum	−11	−64	−12	4.54*
Deactivations				
1. L precuneus	−4	−64	28	7.55***
2. R precuneus	8	−45	32	7.48***
3. L middle temporal gyrus	−41	−64	20	7.49***
4. L superior frontal gyrus	−26	26	52	7.20***
5. Inferior frontal gyrus	0	68	−4	6.84***
6. R superior temporal gyrus	52	−56	12	5.90***
7. L lingual gyrus	−15	−86	−8	5.80***
8. R superior temporal gyrus	52	−4	0	5.76***
9. R inferior frontal gyrus	26	68	12	5.43**
10. L transverse temporal gyrus	−34	−30	12	5.39**
11. R inferior frontal gyrus	11	60	4	5.23**
12. R superior temporal gyrus	41	−8	0	5.08**
13. R lingual gyrus	22	−86	−8	5.02**
14. R superior frontal gyrus	30	22	40	4.97**
15. L parahippocampal gyrus	−26	−38	−8	4.72*
16. R insula	38	−22	12	4.71*
17. L precentral gyrus	−56	−4	24	4.45*

* *P* < 0.05, corrected for multiple comparisons.
** *P* < 0.01, corrected for multiple comparisons.
*** *P* < 0.001, corrected for multiple comparisons.
R, right hemisphere; L, left hemisphere.

found in the bilateral middle and posterior superior temporal gyrus, lingual gyrus, bilateral parietal lobe insula, bilateral superior and medial frontal gyrus, and left parahippocampal gyrus. This pattern of results was

TABLE II. Significant areas of activation and deactivation for the abstract stimuli vs. baseline comparisons

Region	Talairach coordinates (mm)			Z-score value
	x	y	z	
Activations				
1. L fusiform gyrus	−41	−60	−12	8.02***
2. Cingulate gyrus	0	11	40	7.97***
3. L inferior frontal gyrus	−49	8	32	7.93***
4. R inferior frontal gyrus	52	8	28	7.72***
5. L inferior parietal lobule	−30	−52	40	7.66***
6. R superior parietal lobule	30	−56	48	7.59***
7. R middle frontal gyrus	38	4	52	7.26***
8. R superior temporal gyrus	56	−38	16	7.06***
9. L middle frontal gyrus	−34	0	56	7.05***
10. L inferior frontal gyrus	−30	0	44	6.83***
11. R cerebellum	38	−52	−20	6.69***
12. L middle temporal gyrus	−52	−52	4	6.66**
13. L inferior frontal gyrus	−56	19	16	6.35**
14. L parietal lobe	−41	−34	44	6.23**
15. L insula	−30	34	4	6.04**
16. R cerebellum	4	−71	−16	5.87*
17. R fusiform gyrus	38	−74	−12	5.59*
18. R superior temporal gyrus	56	11	0	5.00*
19. R inferior frontal gyrus	41	26	0	4.64*
Deactivations				
1. L middle temporal gyrus	−41	−68	28	7.77***
2. Precuneus	0	−52	36	7.76***
3. L middle temporal gyrus	−41	−64	20	7.70***
4. L precuneus	−8	−64	20	7.69***
5. L superior frontal gyrus	−26	26	52	7.38***
6. Inferior frontal gyrus	0	71	0	7.26***
7. R lingual gyrus	22	−82	−8	6.48***
8. R superior temporal gyrus	52	−4	−4	5.99***
9. L parahippocampal gyrus	−22	−41	−8	5.75**
10. R superior temporal gyrus	49	−56	12	5.72**
11. L precentral gyrus	−56	−8	12	5.41**
12. R superior frontal gyrus	30	22	40	5.23**
13. R insula	41	−11	12	5.15**
14. R middle temporal gyrus	45	−68	28	5.03**
15. L lingual gyrus	−19	−86	−8	4.92*
16. L precentral gyrus	−52	−11	28	4.91*
17. R transverse temporal gyrus	38	−26	12	4.85*

* $P < 0.05$, corrected for multiple comparisons.
** $P < 0.01$, corrected for multiple comparisons.
*** $P < 0.001$, corrected for multiple comparisons.

nearly identical for both the baseline vs. concrete stimuli and the baseline vs. abstract stimuli (see Tables I and II).

DISCUSSION

The behavioral performance data from this study confirm the previously established finding that con-crete words are recognized more quickly and accurately than abstract words. Our fMRI data indicate that both the left and the right hemisphere are engaged during the recognition of both concrete and abstract words, but the right hemisphere is more engaged in the processing of abstract words than of concrete words.

Our findings with regard to areas that are similarly activated during processing of concrete and abstract words largely replicate the findings of previous functional imaging studies of lexical decision-making that did not address the issue of differences between the processing of concrete and abstract words. In particular, for both concrete and abstract words, a set of left hemisphere cortical sites including the fusiform, inferior parietal, middle temporal, inferior frontal, and middle frontal gyri was activated. All of these left hemisphere cortical sites, except the middle frontal gyrus, were identified by Rumsey et al. [1997] in a study of cerebral activation during word recognition. Furthermore, we observed increased activity in sites such as the cingulate cortex, premotor cortex, and cerebellum that would be expected to be active during tasks that entailed a decision to make a motor response.

In addition, we found that the right posterior temporal lobe was engaged during lexical decisions for both abstract words and concrete words. The peak activation for both word types was at an identical site in the posterior superior temporal gyrus, although the statistical significance of the activation was greater for the abstract words. In a study of lexical decision using two different durations of stimulus presentation, Price et al. [1994] found activation at a right middle temporal site approximately 28 mm inferior to the site at which we observed peak activation, when stimuli were presented for 150 msec. However, there was no significant activation in this vicinity when stimuli were presented for 1,000 msec, suggesting that increasing task difficulty, in a way that demands more attention to the task, might be associated with greater right temporal activation. In our study, words were presented for 300 msec.

TABLE III. Significant areas of activation for the abstract stimuli vs. concrete stimuli comparisons

Region	Talairach coordinates (mm)			Z-score value
	x	y	z	
Activation				
1. R superior temporal gyrus	56	11	0	5.66*

* $P < 0.001$, corrected.

Price et al. [1994] did not report the relative proportions of concrete and abstract words presented, and the aim of their study did not include addressing the issue of differences between patterns of cerebral activity associated with processing concrete and abstract words. Bookheimer et al. [1995] also reported a bilateral posterior superior temporal lobe activation for reading aloud concrete nouns. However, Bookheimer et al. [1995] observed activation only in the left temporal lobe when subjects were required to silently read concrete nouns.

The principle objective of our study was to examine the differences in cerebral activity during recognition of concrete and abstract words. In particular, we proposed that the processing of abstract words would be associated with greater right-sided activation than the processing of concrete words. In accordance with our hypothesis, right-sided activation was greater for abstract words than for concrete words, especially in the right anterior temporal and frontal cortex. The direct comparison between the cerebral activity associated with processing abstract stimuli and that associated with processing concrete stimuli demonstrated a significant difference in the anterior part of the right superior temporal gyrus. There was also greater activity during processing of abstract stimuli in the right inferior frontal gyrus. This finding is similar to that reported by Beauregard et al. [1997]. They found that passive viewing of abstract words, but not concrete words, activated the right prefrontal cortex. We note that Beauregard et al. [1997] found that this right inferior frontal gyrus activation for abstract words became insignificant when the effects of anticipation, receiving instructions, preparing the task, attention, and memory were removed. D'Esposito et al. [1997] also found activation of the right superior frontal gyrus during passive viewing of abstract words, when compared with active processing of concrete words.

While the lexical decision task performed by our subjects did not explicitly demand processing of the meaning of words, it is likely that some semantic processing occurred. The observation that the recognition of concrete words is more rapid and accurate than that of abstract words strongly implies that execution of a lexical decision is associated with performance of the semantic processing required to distinguish between concrete and abstract words. Furthermore, the observation that concrete words are recognized more quickly suggests that the relevant semantic processing is more rapid for concrete words. Since slower processing implies the involvement of more extensive neural pathways, the slower recognition of abstract words suggests the hypothesis that more extensive semantic processing is required for the recognition of abstract words.

The observation by Schwanenflugel and Stowe [1989], that the provision of additional contextual information can reduce the difference between concrete and abstract words in speed of recognition, supports the hypothesis that recognition of abstract words in the absence of external contextual clues requires relatively extensive semantic processing in order to derive contextual clues from stored semantic information. If this hypothesis is correct, our findings suggest that the relevant semantic processing engages the right anterior temporal and/or frontal cortex.

There is substantial evidence that both left and right temporal lobes are engaged during semantic processing. For example, Pugh et al. [1996] reported bilateral activation of the superior temporal gyrus during a semantic categorization task. The method of analysis reported by Pugh et al. [1996] does not permit precise localization of the area of activation. Nonetheless, they reported that the superior temporal region that they examined included Brodmann area 38, which is located in the anterior temporal cortex and embraces the site at which we observed greater right-sided activation during processing of abstract words relative to concrete words. In a recent study employing event-related fMRI techniques, we demonstrated that the anterior part of the right superior temporal gyrus exhibits enhanced activity during the processing of the final word of sentences to determine whether or not that final word was semantically congruent with the context established in the preceding part of the sentence [Unpublished observations].

In summary, we have demonstrated the cortical areas in the right hemisphere show greater activation when processing abstract word stimuli than when processing concrete word stimuli during a lexical decision task. In particular, our finding that the anterior part of the right superior temporal gyrus is more active during the recognition of abstract words, compared with concrete words, is consistent with the hypothesis that the recognition of abstract words is slower and less accurate because more extensive semantic processing, engaging the right superior temporal gyrus, is required for the recognition of abstract words.

Our findings are inconsistent with the dual-coding theory, according to which recognition of concrete words, but not abstract words, can be achieved by employing an image-based right hemisphere process in addition to left hemisphere processing [Paivio, 1991]. Contrary to the formulation by Paivio [1991] of the dual-coding hypothesis, our findings indicate that the right hemisphere is more heavily engaged during the processing of abstract words. However, it should be noted that evidence from some studies of event-

related potentials (ERPs) supports the dual-coding theory. For example, Kounios and Holcomb [1994] found increased negativity of the scalp potential in both the 300–500-msec time window and the 500–800-msec time window after presentation of concrete words compared with abstract words, during a lexical decision task. The increase in negativity during processing of concrete words was even greater during a semantic decision task in which the participants were required to decide whether or not a word was concrete or abstract. Furthermore, the difference between the potentials elicited by concrete and abstract words was greater at right-sided electrodes. Since the negative component in the scalp potential that reaches a maximum around 400 msec after visual presentation of a word, usually known as the N400 component, is thought to reflect semantic processing [Kutas and Hillyard, 1980], the observations of Kounios and Holcomb [1994] imply that the recognition of concrete words is associated with greater semantic processing, especially in the right hemisphere.

We also found that N400 amplitude is greater for concrete words than for abstract words, but in our study, which used a different reference montage, the difference in amplitude of the N400 component was greatest at left-sided electrode sites [Kiehl et al., in press]. This finding illustrates the possibility that the location of the reference electrode can determine the side on which the N400 amplitude is maximal. Nonetheless, this finding supports the hypothesis that concrete words are associated with greater semantic processing, provided the negativity in the vicinity of 400 msec reflects semantic processing. It should also be noted that tasks requiring a decision usually produce a large positive ERP component in the 300–600-msec time window (i.e., P3 component). It is possible that the increased amplitude of N400 for concrete words does not indicate increased semantic processing but rather reflects a lesser ERP positivity because the decision is easier for concrete than for abstract stimuli.

Overall, our findings, together with the findings of previous PET, fMRI, and ERP studies, indicate that both left and right hemispheres play an important role in word recognition. Furthermore, the majority of the evidence indicates differences in the relative contributions of the two hemispheres to the recognition of concrete and abstract words. However, the PET data of Beauregard et al. [1997], and the fMRI data of D'Esposito et al. [1997] and of this study, indicate that the right hemisphere plays a relatively greater role in processing abstract words, whereas the ERP data of Kounios and Holcomb [1994] indicate that the right hemisphere plays a greater role in processing concrete

words. Further investigation of the relationship between the N400 measured in ERP studies, and of the increase in cerebral activity detected by fMRI during lexical and semantic processing, is required to clarify this apparent contradiction.

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