

Phonological Decoding Involves Left Posterior Fusiform Gyrus

Nicole A.E. Dietz,¹ Karen M. Jones,¹ Lynn Gareau,¹ Thomas A. Zeffiro,²
and Guinevere F. Eden^{1*}

¹Center for the Study of Learning and Department of Pediatrics, Georgetown University Medical Center, Washington, DC

²Center for Functional and Molecular Imaging and Department of Neurology, Georgetown University Medical Center, Washington, DC

Abstract: Aloud reading of novel words is achieved by phonological decoding, a process in which grapheme-to-phoneme conversion rules are applied to “sound out” a word’s spoken representation. Numerous brain imaging studies have examined the neural bases of phonological decoding by contrasting pseudoword (pronounceable nonwords) to real word reading. However, only a few investigations have examined pseudoword reading under both aloud and silent conditions, task parameters that are likely to significantly alter the functional anatomy of phonological decoding. Subjects participated in an fMRI study of aloud pseudoword, aloud real word, silent pseudoword, and silent real word reading. Using this two-by-two design, we examined effects of word-type (real words vs. pseudowords) and response-modality (silent vs. aloud) and their interactions. We found (1) four regions to be invariantly active across the four reading conditions: the anterior aspect of the left precentral gyrus (Brodmann’s Area (BA) 6), and three areas within the left ventral occipitotemporal cortex; (2) a main effect of word-type (pseudowords > words) in left inferior frontal gyrus and left intraparietal sulcus; (3) a main effect of response-modality (aloud > silent) that included bilateral motor, auditory, and extrastriate cortex; and (4) a single left hemisphere extrastriate region showing a word-type by response-modality interaction effect. This region, within the posterior fusiform cortex at BA 19, was uniquely modulated by varying phonological processing demands. This result suggests that when reading, word forms are subject to phonological analysis at the point they are first recognized as alphabetic stimuli and BA 19 is involved in processing the phonological properties of words. *Hum Brain Mapp* 26:81–93, 2005. © 2005 Wiley-Liss, Inc.

Key words: reading; phonological processing; decoding; words; pseudowords; fMRI

INTRODUCTION

Functional neuroimaging studies of pseudoword (pronounceable nonword) reading are a prominent part of ongoing efforts to understand the neural basis of reading [Cappa Perani et al., 1998; Fiebach et al., 2002; Fiez et al., 1999; Hagoort et al., 1999; Jobard et al., 2003; Joubert et al., 2004; Mechelli et al., 2003; Petersen et al., 1990; Price et al., 1996; Rumsey et al., 1997a] and its disorders [Brunswick et al., 1999; Rumsey et al., 1997b]. Decoding of unfamiliar nonwords necessitates sublexical phonological processing, whereby the conversion of the visual word representation into its abstract phonological code is accomplished by the use of grapheme-to-phoneme correspondence rules. Relative to reading familiar words, pseudoword reading places a greater demand on the phonological processing system; even though real words can be read via assembled phonology, pseudoword reading can only be accomplished via this

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*Correspondence to: Guinevere Eden, Center for Study of Learning, Georgetown University Medical Center, Building D, Suite 150, Box 571406, 4000 Reservoir Rd., NW, Washington, D.C. 20057-1406. E-mail: edeng@georgetown.edu

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indirect/sublexical procedure. Phonological processing problems, especially those requiring sublexical analyses, are the hallmark of some cases of acquired reading disorders [Friedman et al., 1993; Leff et al., 2001] and account for many of the difficulties encountered by children and adults with the reading disability developmental dyslexia [Vellutino et al., 2004]. Better knowledge of the neural bases of reading and sublexical phonological processing could facilitate the early identification of reading disabilities and the development of effective reading remediation strategies.

Various models and theories of word recognition offer accounts of the neural mechanisms that may underlie the transformation of orthography to phonology in reading. These theories were largely introduced to explain the different patterns of reading disabilities observed among patients with acquired dyslexias [Warrington and Shallice, 1980]. Some patients had intact word reading (regular and exception words) accompanied by difficulty in reading pseudowords (phonological dyslexia), while others could read pseudowords and regular real words, but were unable to read exception words (surface dyslexia). The dual-route model of word reading arose to explain this double dissociation [Coltheart et al., 1993]. According to this model, known words have stored lexical representations that can be very quickly accessed via a memory-based lexical route of reading, whereas pseudowords must undergo a more methodical process of grapheme-to-phoneme conversion (GPC) using a rule-based sublexical route. A model with three routes for reading was developed based on the observation of a patient who could correctly read regular words, exception words, and pseudowords, but whose comprehension was poor [Gerhand, 2001; Southwood and Chatterjee, 2000]. Alternatively, a computational approach in the form of parallel distributed processes (PDP) describes a system of interconnected word processing units linked together in parallel [Seidenberg and McClelland, 1989]. Consequently, the same neural network is used for reading whether or not the word is familiar. Word exposure modulates the connection strengths between phonological and orthographic units such that frequently encountered words are phonologically decoded more rapidly and accurately than unknown words.

Neuroanatomical correlates of these reading models have been examined and tested using functional imaging techniques including positron emission tomography (PET), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI). The contrast of pseudoword with real word reading differs in phonological demands and elicits an increase in activity in left posterior superior (“dorsal stream”) cortical areas including the lateral inferior parietal and posterior superior temporal cortices [Hagoort et al., 1999; Herbster et al., 1997; Price et al., 1996; Pugh et al., 1996; Rumsey et al., 1997a; Simos et al., 2002]. Dyslexic readers, having impaired phonological processing abilities, show underactivation of these regions relative to typical readers during phonological processing tasks [Brunswick et al., 1999; Eden et al., 2004; Rumsey et al., 1997a; Shaywitz et al., 1998]. Based on these findings, the left inferior parietal/

posterior superior temporal cortex has been purported to be the substrate subserving the assembled, sublexical, or indirect route of the dual-route model, where GPC rules are applied to decode words. In addition, the dorsal left inferior frontal cortex has also been implicated in supporting phonological processing. This finding appears to be most consistent in studies of aloud reading [Brunswick et al., 1999; Fiez et al., 1999; Hagoort et al., 1999; Herbster et al., 1997; Poldrack et al., 1999; Pugh et al., 1996; Rumsey et al., 1997a; Zurowski et al., 2002]. The exact role of the inferior frontal cortex is likely to be more complex as semantic processing also invokes activity here, but in regions ventral and posterior to those found during phonological processing [Fiez et al., 1999; Gabrieli et al., 1998].

Familiar, frequently encountered words and irregularly spelled “sight” words that make little demand on sublexical phonological processing have been shown to activate left posterior inferior areas (inferior occipitotemporal cortex and fusiform gyrus), suggesting perhaps that this ventral stream houses the direct, lexical route of reading [Cohen et al., 2000; Fiez et al., 1999; Kiehl et al., 1999; Paulesu et al., 2000]. However, not all brain imaging studies support the idea of two routes. For example, contrary to predictions from a dual-route model, multiple studies have shown activation of this ventral region when processing pseudowords [Brunswick et al., 1999; Paulesu et al., 2000; Price et al., 1996; Xu et al., 2001]. Consequently, it has been argued that these findings of simultaneous activity in multiple brain regions are more consistent with either a connectionist parallel distributed processing (PDP) model of reading [Seidenberg and McClelland, 1989] or other more extensive serial models.

Some of the inconsistencies reported among neuroimaging studies have been attributed to experimental parameters or statistical limitations [Mechelli et al., 2003]. Specifically, opinions regarding which cognitive model provides the best description of the neural representation have been divided, with some claiming evidence for the dual-route model [Fiebach et al., 2002; Jobard et al., 2003; Joubert et al., 2004] and others for connectionist models [Herbster et al., 1997; Rumsey et al., 1997a]. However, in this debate surprisingly little attention has been given to the importance of aloud reading. Instead, silent and aloud reading are often assumed to be interchangeable when making cognitive inferences about the neural basis of reading or phonological processing. Further, the advent of fMRI technology has prompted a disproportionate use of tasks that avoid spoken paradigms, favoring manual responses during lexical decision or silent reading tasks because of technical constraints. As a result, silent reading studies greatly outnumber aloud reading studies due to the concern that speech-induced movements are not compatible with the need to minimize motion-related artifacts.

However, it has been demonstrated that neural activity underlying aloud word reading is not the equivalent of silent reading activity with the addition of related motor and auditory activity [Bookheimer et al., 1995; Huang et al.,

2001]. In fact, when reading aloud vocalization is not initiated until the computation of phonology is complete [Rastle et al., 2000; Seidenberg and McClelland, 1989]. Hence, reading aloud maximally elicits activation of the phonological processing system in a way that silent reading does not [Barch et al., 1999; Huang et al., 2001]. As a consequence, the use of different response modalities (silent vs. aloud reading) will draw on different neural substrates subserving reading [Price et al., 1994; Rumsey et al., 1997a]. These findings from PET studies demonstrate the necessity to include both conditions in future brain imaging studies of reading and phonological processing. To date, only three neuroimaging studies have incorporated both aloud and silent reading to investigate phonological processing [Brunswick et al., 1999; Hagoort et al., 1999; Rumsey et al., 1997a]. Two of these studies involved overt pronunciation of single words, but the comparison task entailed decision-making (phonological or feature) and hence did not allow for a direct comparison. A PET study by Hagoort et al. [1999] employed the same reading tasks for both the aloud and silent conditions. Native German speakers were scanned as they read real German words and pseudowords aloud and silently, but an interaction analysis of response-type (aloud and silent) and lexicality (real words and pseudowords) was not provided. Further, the German language has a relatively transparent orthography (a regular one-to-one correspondence between words' spellings and their pronunciations), whereas English has an opaque (or deep) orthography. Generalization of these results from German to English may therefore be limited and underscores the need for further studies that directly address reading English words and pseudowords aloud.

Taken together, there is a need to examine brain mechanisms related to aloud and silent reading in the English language. To address this question in the context of the neural mechanisms underlying phonological processing in reading, we employed a two-by-two experimental paradigm that placed differential demands on phonological decoding under overt and covert reading conditions in order to elicit differential activation of their corresponding neural substrates. Pseudoword decoding puts more stress on phonological processing than real word reading, as nonwords can only be decoded using addressed phonology, whereas real words can be read either via addressed phonology or the use of the direct lexico-semantic route. Aloud reading also puts greater demands on phonological processing than reading silently, as the phonological codes need to be represented in their entirety in order to pronounce the word. We used fMRI to detect task-related signal changes while adult monolingual English speakers read words and pseudowords aloud and silently. An interleaved data acquisition technique was used to minimize magnetic susceptibility and motion artifacts caused by aloud word reading [Eden et al., 1999]. The aim of our study was not to verify any particular model of reading but to develop a more comprehensive understanding of the neural mechanisms of phonological processing under conditions of aloud and silent reading.

SUBJECTS AND METHODS

Subjects

Sixteen subjects (nine female, seven male; mean age 31.1 years; age range, 20.9–39.5) participated in this study. Subjects were right-handed as determined by the Edinburgh Handedness Inventory [Oldfield, 1971] and were native speakers of English. Subject exclusion criteria included bilingualism, claustrophobia, nicotine or other drug use, a history of head injury, a known family history of psychiatric, neurological, or developmental disorders involving first-degree relatives, presence of metal fragments in the body, or pregnancy. Subjects had normal or corrected vision, normal local and global stereopsis, and normal color vision [Ishihara, 1996]. Attention Deficit/Hyperactivity Disorder was excluded using the abbreviated Wender Utah Rating Scale [Ward et al., 1993]. Reading was evaluated by a comprehensive battery of neuropsychological tests that included real word and pseudoword reading as well as phonological awareness skills. Results of these behavioral measures were normal or above for all subjects. Subjects were paid for their participation and gave written informed consent in accordance with the Georgetown University Medical Center Institutional Review Board.

Experimental Tasks and Design

Subjects participated in two 12-min experimental runs during which they read 1) silently (without moving the lips, tongue, or jaw), and 2) aloud. Both runs contained alternating blocks of real words and pseudowords and consisted of 10 48-s task periods and 10 24-s rest (fixation) periods. The two runs were pseudorandomized in order of presentation with two additional runs collected for the purpose of a different study.

To minimize any magnetic susceptibility artifacts caused by potential head and jaw movements associated with reading [Birn et al., 1998], task performance (reading) coincided with a time during the block when the gradients were turned off [Eden et al., 1999]. These trials were interleaved with periods of image acquisition, with the assumption that the 4–8-s delay in the hemodynamic response [Bandettini et al., 1992; Kwong et al., 1992; Logothetis, 2001] would allow detection of the blood oxygenation-level dependent (BOLD) contrast generated by the previously performed task. In this way, the use of a TR (repetition time) of 12 s yielded four brain volumes (time points) during each 48-s task block (see Fig. 1). Within a word reading epoch, words or pseudowords were presented for 200 ms and followed by a 2450 ms response interval during which subjects viewed a fixation crosshair. Three words were presented within a trial, each trial lasting 8 s. The epoch was completed after the fixation crosshair was displayed for 4,050 ms, while a whole-brain volume was acquired, hence resulting in each epoch lasting 12 s (equal to the TR). Three more epochs occurred, so that a total of four brain volumes were acquired within 48 s, before a 24-s fixation block ensued, wherein subjects viewed a crosshair while two brain volumes were acquired.

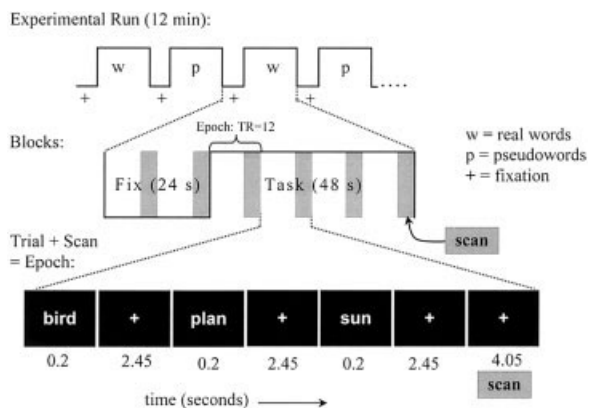


Figure 1.

Experimental paradigm. Subjects underwent two experimental runs: reading single words (nonwords and real words) aloud and silently. No stimuli were repeated across the two runs. Each run consisted of blocks during which subjects read words (48 s) or blocks during which they only fixated (24 s). During the reading blocks three words (or nonwords) were presented during an 8-s trial, followed by a 4-s acquisition period. Each block contained four epochs (trial plus acquisitions) each epoch lasting 12 s, the duration of the TR. Real word or pseudoword trials consisted of a 200 ms word presentations, followed by a pause of 2450 ms in which a crosshair was presented and the subjects responded aloud or silently.

A total of 60 data points were collected during each 12-min experimental run: 20 each for the word task, pseudoword task, and fixation condition.

Real words were regularly spelled, single-syllable English nouns of midrange frequency (three to five letters in length, median of four letters; mean MRC Psycholinguistic Database ratings: concreteness, 574.4 (range 270–642); familiarity, 552.1 (range 446–645); Kucera-Francis written frequency, 60.6 (range 20–431)). Words were matched for concreteness, familiarity, and frequency across word lists. Pseudowords were generated from the real words by changing one or more letters until novel words were formed (e.g., *norp*, *saff*, *janth*, and *kig*), and were matched with real words for letter length and number of syllables. Pseudowords were reviewed by three native speakers of English and were discarded from the list if determined to be unpronounceable, were pseudohomophones of real words, or had a close orthographic resemblance to a real word. Sixty words and 60 pseudowords were presented in each experimental run. No word or pseudoword was repeated throughout the course of the entire experiment. The stimuli were displayed in white lower-case Arial font on a black background.

fMRI Data Acquisition

All MRI data were acquired on a 1.5 T Siemens Magnetom Vision system with a circularly polarized head coil. The visual stimuli were projected onto a screen mounted on the top of the

head coil. An angled mirror affixed to the head coil allowed a clear view of the screen and stimuli. Each whole-head volume was acquired in four seconds with echo planar imaging (EPI) acquisition parameters as follows: 40 ms echo time (TE), 12-s repetition time (TR), 64×64 matrix, 230 mm field of view (FOV), 46 axial slices, 3.0 mm slice thickness, 0.6 mm gap, resulting in 3.6 mm cubic voxels. For both of the runs a total of 63 frames (brain volumes) were acquired. The first three frames for each experimental run were discarded to achieve equilibrium in longitudinal relaxation.

Data Analysis

Image analysis was carried out using MEDx (Sensor Systems, Sterling, VA) and custom scripts. Image time series were motion-corrected to the mean intensity image using the Automated Image Registration (v. 3.08) rigid body realignment algorithm [Woods et al., 1998a,b]. Gaussian spatial smoothing was applied using a low-pass filter with a full-width at half-maximum of 7.2 mm (two times the voxel size) and a 9×9 mm convolution kernel. Global spatial variations in global image intensity were corrected with ratio normalization. To remove local low frequency signal drift, each time series was processed with a high-pass temporal Butterworth filter with a period of 144 s (equal to two times the task period). For each subject the mean image was calculated for each task condition (word aloud, word silent, pseudoword aloud, pseudoword silent, fixation) and mean difference images were generated by subtracting the fixation condition from each task condition.

To determine regions of increased task-related signal change for each condition relative to fixation at the group level, single-group *t*-tests were performed. These analyses resulted in *t*-statistic maps that were then converted to Z-score images and thresholded at $Z > 3.1$ ($P < 0.001$, uncorrected). The transformation matrix obtained when transforming the mean EPI image from a specific run to the EPI template (provided within Statistical Parametric Mapping, SPM96, Wellcome Department of Cognitive Neurology, London) was saved and used to shadow transform the statistical maps of various contrasts (e.g., pseudoword minus fixation) into the MNI 305 atlas space. The coordinates of the significant foci were converted from MNI space to a coordinate system corresponding with the stereotaxic atlas of Talairach and Tournoux [1988], using equations derived by Brett [1999]. For all figures displayed in the Results section, images are portrayed in the radiological convention, with the left side of the brain (L) represented on the right side of the figure and anterior towards the top of the figure. Using the GLM module within MEDx, an analysis of variance (ANOVA) was performed between the mean difference images of the four contrasts in order to identify the main effects of word-type (pseudowords > real words) and response-modality (aloud > silent), and the interaction of word-type with response-modality. The significance threshold employed was $Z > 3.1$ ($P < 0.001$).

RESULTS

Behavioral Performance

Accuracy of the pronunciation of real words and pseudowords was determined for the overt condition. Pseudowords were judged as correct if the pronunciation corresponded to English grapheme-to-phoneme rules; some pseudowords had more than one acceptable pronunciation. As expected, the mean accuracy for real words for the 15 subjects analyzed was 99.5%, significantly greater than the mean pseudoword accuracy of 94.5% ($P < 0.003$).

Functional MRI Results

Several contrasts were carried out in this study. We present results from: (1) the contrasts of each individual task (i.e., aloud pseudoword reading, aloud real word reading, silent pseudoword reading, and silent real word reading) relative to the viewing of a fixation point; (2) the conjunction of these four reading contrasts to reveal areas of activity common to all tasks; (3) the main effect of pseudoword vs. real word reading, when collapsing the aloud and silent conditions (main effect of word-type); (4) the main effect of aloud vs. silent reading, when collapsing pseudoword and real word reading (main effect of response-modality); and (5) the interaction of word-type with response-modality.

1. All Tasks vs. Fixation

We first subtracted viewing of a fixation point from each reading condition to visualize the global pattern of neural activity elicited by each reading task. Figure 2 displays representative transverse sections of the results of the single-group *t*-tests showing regions of increased task-related signal for each condition (aloud pseudoword, aloud real word, silent pseudoword, and silent real word reading) relative to fixation. Visual inspection of the activation maps reveals the two aloud reading tasks elicited considerably more activity, both in intensity and extent, than the silent tasks, particularly in the primary motor (Brodmann's Area (BA) 4) and auditory cortices (BA 38, 21/22). Not surprisingly, for each task the overall intensity and extent of activity tended to be left hemisphere lateralized.

2. Effects Common to All Reading Conditions: Aloud Pseudoword, Aloud Real Word, Silent Pseudoword, and Silent Real Word

The statistical maps generated as described above were submitted to a conjunction analysis to identify regions that showed increased task-related signal change across all four reading conditions relative to their respective fixation baseline: the left anterior precentral gyrus in BA 6, and three regions within the left fusiform gyrus, one located within anterior BA 37, another in the mid-fusiform region of BA 37, and the third posteriorly in BA 19. These are depicted in Figure 2, and Table I provides the corresponding spatial coordinates of the center of mass for each region.

3. Main Effect of Word-Type: Pseudowords > Real Words

The main effect of lexicality was determined by collapsing across aloud and silent conditions. A main effect of pseudoword reading relative to reading real words was observed in two regions within the left inferior frontal gyrus (BA 44/6 and BA44) and an area in the left intraparietal sulcus (IPS, BA 7). As can be seen in Figure 3, the left IPS region demonstrated an especially prominent effect (with corresponding spatial coordinates provided in Table II).

4. Main Effect of Response-Modality: Aloud > Silent

Table III and Figure 4 show the main effect of reading aloud relative to silent reading (with word-type collapsed). Reading aloud elicited large increases in the BOLD-contrast response bilaterally within the primary motor (BA 4), premotor (BA 6), presupplementary motor areas (BA 6, in the medial superior frontal gyrus), bilateral auditory cortex within the superior temporal gyri (BA 42/22), and bilateral posterior fusiform cortex (BA 19). The main effect of aloud reading also included two regions of the left hippocampal cortex (BA 36, 28), midline thalamus, and the left putamen.

5. Interaction of Word-Type With Response-Modality

Using the mean difference images of the four contrasts generated as described above, an ANOVA was performed to reveal regions demonstrating an interaction effect of word-type (pseudowords vs. real words) and response-modality (aloud vs. silent reading). The interaction revealed a single significant locus (see Fig. 5), in the left posterior fusiform gyrus (BA 19, peak voxel $-22, -73, -13$; peak Z-score = 3.59, $P < 0.0002$). A post-hoc analysis showed that the activity here for aloud pseudoword reading was greater than for aloud real word reading, silent pseudoword reading, and silent real word reading ($P < 0.05$). We confirmed that the area was located in the extrastriate/fusiform cortex by first registering and then overlaying each individual subjects' statistical maps with their own anatomical T1-weighted image.

DISCUSSION

In this study we investigated the neural mechanisms of phonological decoding in the context of aloud and silent single word reading. Four reading conditions were used, each of which varied from the other in the demands placed on phonological processing: silent real word reading, silent pseudoword reading, aloud real word reading, and aloud pseudoword reading. The lexical unfamiliarity of pseudowords invokes addressed phonology. Phonological processing is also invoked by aloud reading, as pronunciation obligates access to the complete phonological word form. Hence, the reading of real words and reading

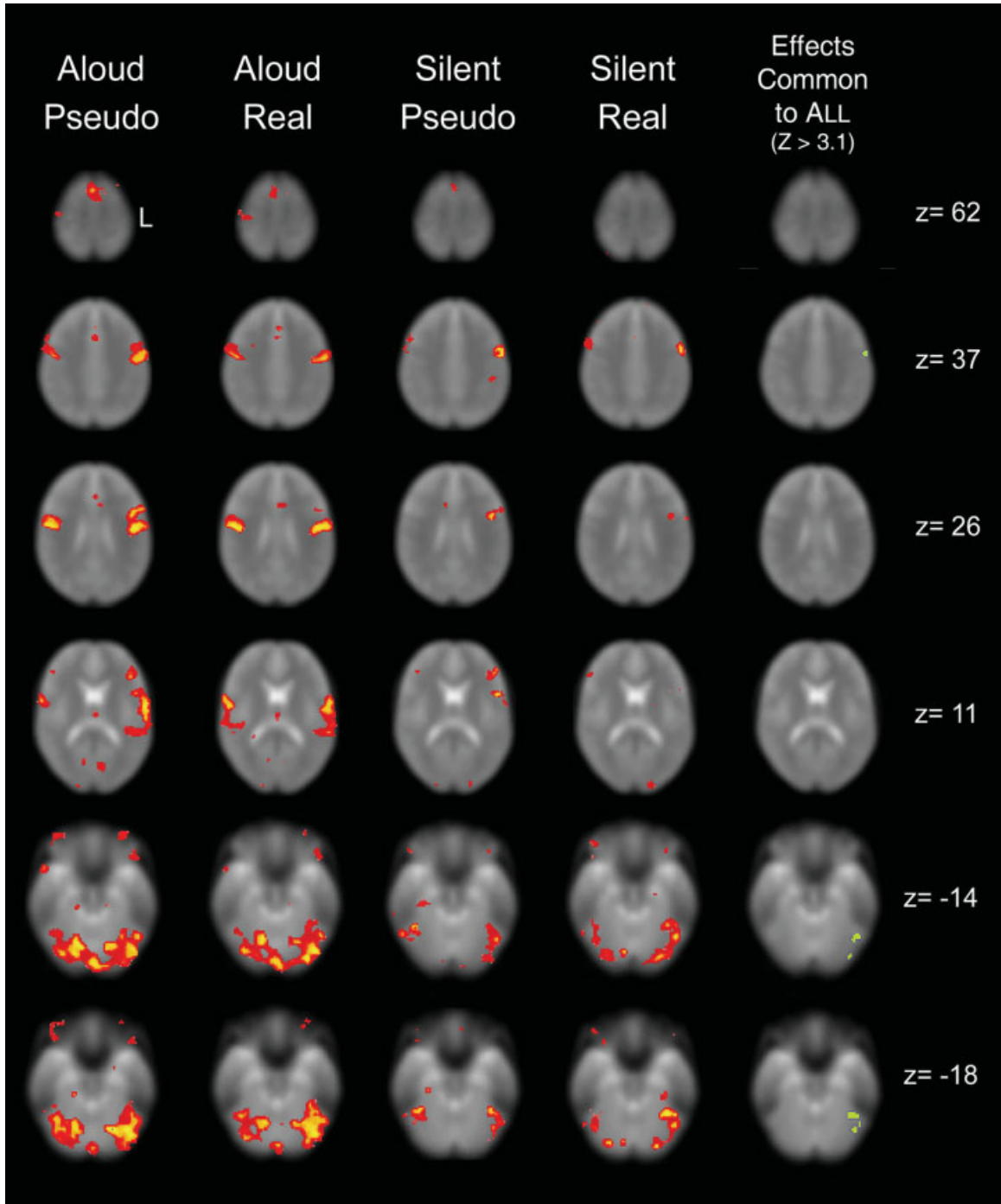


Figure 2.

Transverse sections illustrating areas of significant activity for the four task conditions relative to the fixation baseline. From left to right: aloud pseudoword reading; aloud real word reading; silent pseudoword reading; silent real word reading; and the conjunction of all four tasks showing regions of activity common to all tasks. For all figures the z-coordinate given is in

the coordinate space of the atlas of Talairach and Tournoux [1988]. Images are portrayed in the radiological convention, with the left side of the brain (L) represented on the right side of the figure and anterior is towards to top of the figure. For visualization purposes, activity is displayed at a critical threshold of $Z > 2.33$ ($P < 0.01$, uncorrected).

TABLE I. Regions of activity common to all reading tasks (vs. fixation): aloud pseudoword, aloud real word, silent pseudoword, silent real word

	BA	Cluster Center*			Cluster size (mm ³)
		x	y	z	
L precentral gyrus	6	-54,	1,	36	224
L fusiform gyrus	37	-39,	-44,	-20	368
	37	-45,	-58,	-15	384
	19/18	-38,	-77,	-12	56

* Data are given in Talairach coordinates.

silently served as contrasts for reading pseudowords and reading aloud, respectively. We examined 1) task-related signal change common to the four reading conditions, 2) the main effects of word-type and response-modality, and 3) their interaction. Our central finding was derived from the interaction analysis and revealed a region within the left posterior fusiform cortex (ventral BA 19) that was modulated by increased stress on phonological processing. Hence, this region appears to serve a role in detecting the phonological demands associated with words. It is sensitive to a variety of aspects of phonological processing, including addressed phonology (applying sound-correspondence rules) necessary to decode novel words in the absence of recognition-based experience (pseudowords), and to conditions that necessitate the computation of a complete phonological representation (pronunciation). It is likely that this functional specialization for the phonological attributes of word processing is the end result of reading acquisition, much like the emergence of the “visual word form area” [McCandliss et al., 2003], a region tuned to orthographically legal word forms [Polk and Farah, 2002].

Effects Common to All Reading Conditions

Four cortical regions were active consistently across all reading conditions: the anterior aspect of the left precentral gyrus (BA 6), and three areas within the left ventral occipitotemporal cortex. This consistency, regardless of word-type or response-modality, suggests that these four regions play important roles in reading of regular letter combinations. The ubiquitous presence of activity within the anterior aspect of the left precentral gyrus (i.e., premotor cortex) implies that word reading in general entails some amount of subvocalization, or internal speech. Activation was observed here even for the silent reading task, for which subjects were instructed to read the words to themselves without moving their tongue or jaw, suggesting motor preparation activity regardless of whether or not the words are overtly pronounced.

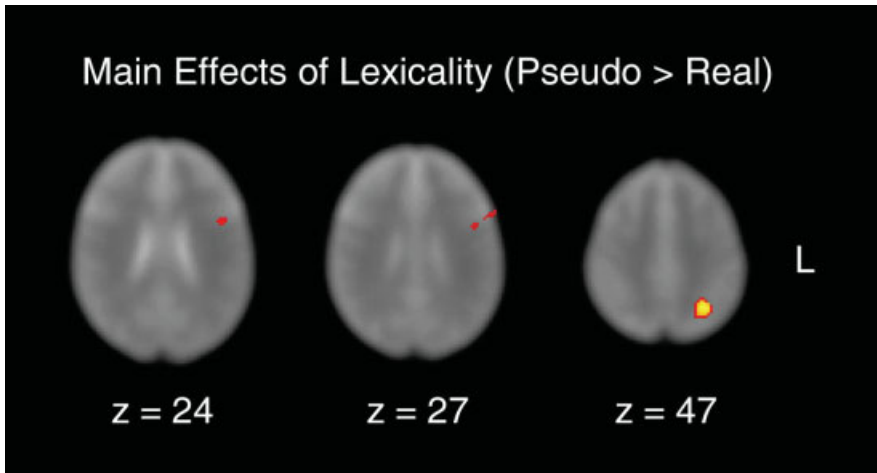
Also active for all reading conditions were three regions of the left ventral occipitotemporal cortex, situated in an anterior-posterior line along the fusiform gyrus. The most posterior region was located in the extrastriate cortex, within BA 19. Despite its early placement within the visual processing

stream, this region has been shown to demonstrate a preferential response to alphabetic stimuli (words and consonant strings) over checkerboards [Cohen et al., 2003]. The second locus was within the mid fusiform gyrus at BA 37, the location of the putative visual word form area (VWFA) described by Cohen and others who have taken note of its very reliable response to orthographically legal word forms invariant of font, case, size, or position [Cohen et al., 2000, 2002]. The VWFA has been shown to respond to pseudowords and real words alike, signifying that its representation of word forms is at a prelexical level. Recent work suggests that the role of the VWFA may be quite sophisticated, serving as a repository for visual-orthographic patterns which serve as recognition units in subsequent encounters of words [Kronbichler et al., 2004]. A region specifically sensitive to letters has been found adjacent (lateral and anterior) to this region and suggests that letters acquire a special object category with respect to BA 37 [Flowers et al., 2004]. The third fusiform region identified in the present study was located anterior to the VWFA. This area may receive afferent information from the more posterior regions of BA 37 and have a role in initiation of more complex, higher-level word processing such as semantic access [Moore and Price, 1999].

Main Effect of Word-Type: Pseudowords > Words

The contrast of pseudowords with words, independent of response-modality, was performed to identify areas of the brain in which activity can be attributed to addressed phonology (necessary to decode words that cannot be read by relying on context or recall). Two foci within the left inferior frontal gyrus and an area in the left intraparietal sulcus were activated by this contrast. A great deal of evidence implicates the left inferior frontal cortex as playing a key role in phonological processing [Bookheimer et al., 1995; Burton et al., 2000; Fiez et al., 1999; Fiez and Petersen, 1998; Hagoort et al., 1999; Herbster et al., 1997; Huang et al., 2001; Newman, 2001; Rumsey et al., 1997a; Xu et al., 2001; Zatorre et al., 1996]. More in-depth investigations of this region have led to the proposal that it has two anatomically distinct functions in reading: the ventral aspect of the inferior frontal gyrus (BA 47/45) appears to be involved with semantic processing, while the dorsal (opercular) inferior frontal gyrus (IFG, BA 44 and 46) aspect is recruited for phonologically effortful tasks [Bokde et al., 2001; Fiebach et al., 2002; Paulesu et al., 1997; Poldrack et al., 1999]. The inferior frontal cortex activity in the present study is located in BA 44, congruent with the putative phonological area. The left IFG has also been implicated in verbal working memory as the possible locus of the rehearsal loop [Paulesu et al., 1993], which could be another source of the activity we see here.

The activity observed in BA 44 for pseudowords (relative to real words) also expanded into BA 6. As noted above, left BA 6 was active during all of our reading tasks, likely reflecting the occurrence of subvocalization activity. The greater activity here for pseudowords relative to words supports the notion that motor planning is involved in the decoding of unfamiliar word forms and

**Figure 3.**

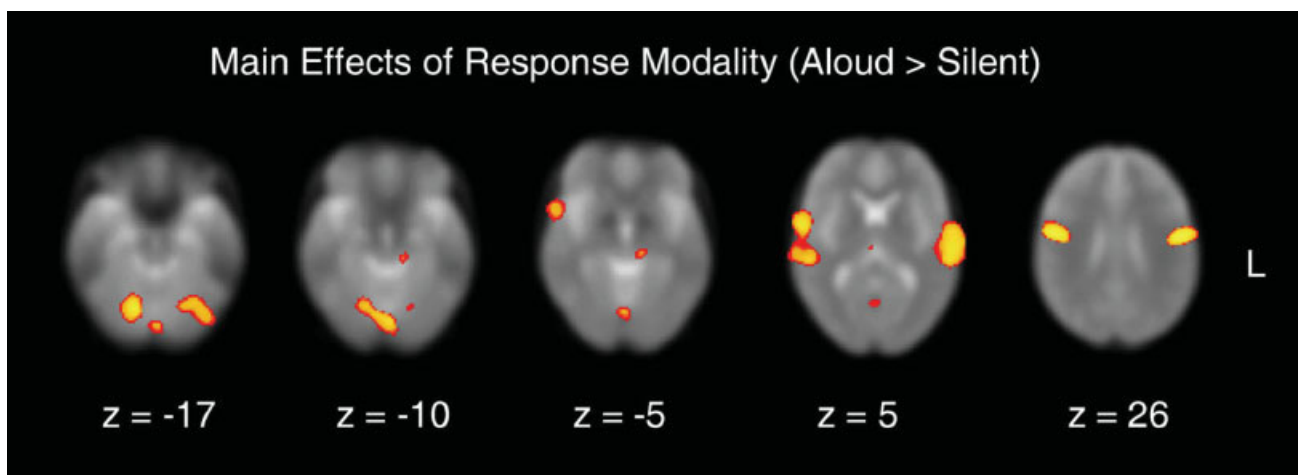
Transverse slices of the three cortical regions showing a main effect of lexicality (pseudowords > real words, collapsed across aloud and silent modalities). The z-coordinate of each slice matches those in Table II.

increases in response to heightened phonological demands. Other studies have reported increases in left precentral gyrus activity with increasing phonological demands [Hagoort et al., 1999], and cognitive models have implicated the motor system in the perception and production of the phonological features of language [Lieberman and Mattingly, 1985].

Motor planning could also be a possible interpretation of the observed activity in the left intraparietal sulcus (BA 7), the third region to demonstrate a main effect of lexicality. The anterior inferior parietal lobule and posterior superior parietal lobule of the left hemisphere contribute to covert motor movement preparation or “motor attention” [Rushworth et al., 2003]. Reading of pseudowords might invoke planning of articulatory sequence movements that correspond to the pronunciation of the word. Alternatively, the greater activation of left IPS for pseudowords (relative to words) could be attributed to the increased demands unfa-

miliar words put on the phonological store of verbal working memory. Several PET studies have identified the left parietal cortex, including the intraparietal sulcus, as the locus of the phonological store [Becker et al., 1999; Paulesu et al., 1993; Ravizza et al., 2004] and parietal cortex has been shown to be underactivated in individuals with developmental dyslexia [Eden and Zeffiro, 1998].

Based on previous studies of phonological processing and phonological assembly, we anticipated activity in posterior aspects of the superior and middle temporal gyri [Bookheimer et al., 1995; Herbster et al., 1997; Price et al., 1996; Pugh et al., 2000; Rumsey et al., 1997a; Simos et al., 2002]. Indeed, dyslexics show a characteristic pattern of reduced activity within these regions [Brunswick et al., 1999; Paulesu et al., 1996; Rumsey et al., 1997b]. The lack of left posterior temporal activity in this study may have been due to the nature of our stimuli; perhaps our pseudowords were not challenging enough to elicit activation here. Greater discrepancy in

**Figure 4.**

Transverse slices showing a main effect of response-modality (aloud > silent, collapsed across pseudoword and real word-types). The maxima of these areas are presented in Table III.

TABLE II. Main effect of lexicality (word-type): pseudowords > real words

	BA	Peak voxel			Peak Z
		x	y	z	
L inferior frontal gyrus	44/6	-57,	15,	27	3.24
L inferior frontal gyrus	44	-44,	7,	24	3.34
L intraparietal sulcus	7	-28,	-54,	47	4.05

phonological difficulty between the pseudowords and real words, such as by using polysyllabic pseudowords with infrequent letter combinations, might have revealed activity in this area. Also, as subjects were reading covertly in the silent condition, it was not possible to obtain performance accuracy. This provides some uncertainty about the demands made by this condition and future studies might address this (at least in part) by using a post-scanning test in which subjects are asked to identify words from a list to indicate how many items they recognize from the scanning session [Turkeltaub et al., 2003]. In any case, reports of activity in the left posterior middle temporal gyrus tend to be intermittent, with some studies, including ours, reporting little or no responses here [Hagoort et al., 1999; Xu et al., 2001]. These variations across different studies raise questions about these regions' precise role in phonological processing and merits further investigation.

**Main Effect of Response-Type:
Aloud Reading > Silent Reading**

The analysis focusing on aloud vs. silent reading (independent of word type) revealed findings that were consistent with earlier studies of aloud word reading [Bookheimer et al., 1995; Hagoort et al., 1999; Turkeltaub et al., 2002]. We

found increased activity in bilateral motor, auditory, and extrastriate visual cortices. The expansive activity underlying aloud reading attests to the fact that reading aloud involves more complex participation of multiple regions other than motor and auditory cortex, and that studies involving silent word reading cannot be substituted for aloud word reading. Our results also demonstrate the utility of interleaved fMRI data acquisition for tasks involving overt speech production to distinguish differences contributed by aloud vs. silent reading.

Interaction Effect of Word and Response Types

The interaction analysis of word-type and response-mode revealed a single locus in the left ventral extrastriate cortex located in posterior fusiform cortex at BA 19. This region was uniquely modulated by increased phonological processing demands invoked by a need for phonological assembly and access to the words' entire phonological code. This finding indicates a special role for left ventral BA 19 in phonological processing.

Ideas and controversies regarding the functional role of the left ventral extrastriate cortex have been evolving with a progression of neuroimaging studies of word form processing. In an early PET study by Petersen et al. [1990], activation in the left medial extrastriate cortex was detected during silent viewing of real words and pseudowords but not consonant letter or false font strings. It was concluded that this region was tuned to orthographically legitimate word forms. Although ventral extrastriate cortex had traditionally been associated with relatively low-level visual processing such as color and form detection, this study and others that ensued supported the idea that the functions of extrastriate cortex are not limited to basic early visual processing. Specifically, left BA 19 and nearby regions have been shown to be more responsive to pseudoword compared to real word

TABLE III. Main effect of response-modality: aloud > silent

	BA	Peak voxel			Peak Z
		x	y	z	
R medial superior frontal gyrus	6	8,	13,	60	5.41
L precentral gyrus	6	-59,	-3,	13	7.25
	4	-51,	-6,	28	7.84
R precentral gyrus	4/6	57,	-1,	13	7.59
	4	51,	-4,	28	7.76
L superior temporal gyrus	38	-51,	15,	-11	4.85
	22/42	-62,	-15,	3	6.94
	22/42	-61,	-27,	7	7.02
R superior temporal gyrus	22	55,	6,	-4	6.18
	22	57,	-27,	3	6.71
L hippocampal	36	-18,	-6,	-33	6.20
	28	-12,	-28,	-10	5.88
L fusiform	19	-34,	-63,	-19	6.81
R fusiform	18/19	16,	-67,	-13	7.34
Midline Thalamus (DM nucleus)		4,	-19,	6	5.23
L putamen		-20,	8,	-2	4.26

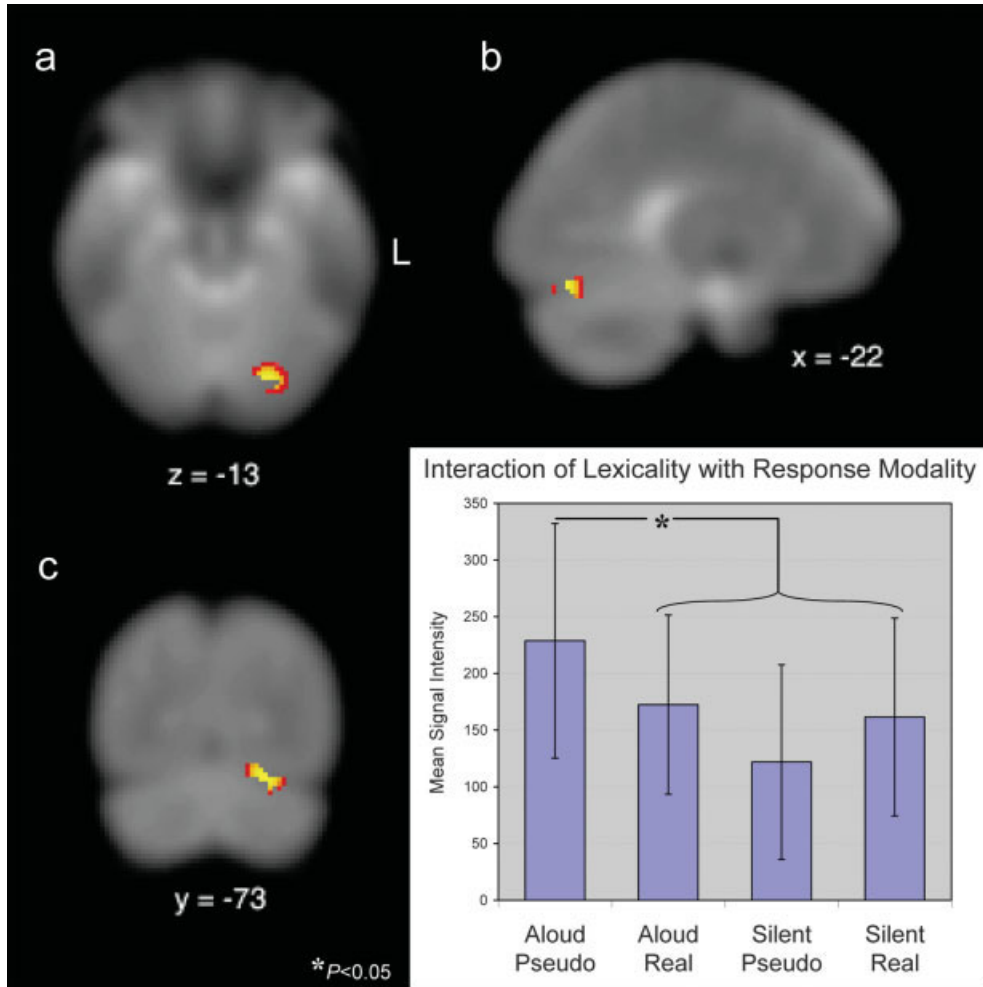


Figure 5.

Transverse (a), sagittal (b), and coronal (c) views of the single region, located in the left posterior fusiform gyrus (BA 19), revealed by the interaction between word-type (lexicality) and response-modality. The bar graph illustrates the relative contribution (mean voxel intensity given in arbitrary units) of each of the four task conditions to the 142-voxel region revealed by the interaction analysis. Post-hoc paired

t-tests showed significantly greater activation for the aloud pseudoword reading condition relative to the aloud real word, silent pseudoword, and silent real word reading conditions ($P < 0.05$). There were no significant differences between the aloud and silent real word reading conditions, or between the silent pseudoword and silent real word conditions.

reading [Hagoort et al., 1999], pseudoword rhyming [Xu et al., 2001], and phonological working memory [Zurowski et al., 2002]. For example, Hagoort et al. [1999] report on a focus (BA 19/37; -34, -55, -11) slightly more anterior to ours that was more active during the reading of pseudowords when contrasted to real words, and more active for aloud compared to silent reading of real words (although this comparison was not significant when repeated for pseudowords). Paulesu et al. [2000] reported a similar result in a sample of English and Italian readers (their coordinates were -48, -68, -6); and Xu et al. [2001] also report a region, more lateral and anterior than the one described in the present study (46, -66, -10), which they identified when subtracting real word rhyming from pseudoword rhyming.

These authors discuss the possibility of this area in mapping orthographic forms to sublexical phonological codes as the result of phonological assembly.

Taken together, these studies not only implicate the left ventral fusiform in an early process where alphabetic stimuli are distinguished from nonalphabetic stimuli [McCandliss et al., 2003; Polk and Farah, 2002], but our results go so far as to suggest the involvement of posterior areas of extrastriate cortex in the initial phonological analysis of written words. The posterior aspect of fusiform gyrus identified in the present study is 20 mm posterior and medial to the visual word form area located in mid-fusiform cortex at BA 37 [McCandliss et al., 2003]. It has been suggested that the VWFA groups letters into “integrated perceptual units” and

is sensitive to abstract information even for newly encountered words [McCandliss et al., 2003; Polk and Farah, 2002; however, see Price and Devlin, 2003]. By analogy, it seems that during aloud reading BA19 is tuned to the phonological properties of words much like the VWFA is tuned to the orthographic properties. The implication of this finding is that phonological analysis of word forms coincides with the early process of recognition of alphabetic stimuli. Our findings build on previous studies that considered phonological processing as a possible explanation for extrastriate cortex activity during reading [Buchel et al., 1998; Polk and Farah, 2002] and rhyming [Xu et al., 2001] tasks. Future studies will be necessary to elucidate the mechanisms that control left ventral BA 19 activity in response to varying levels of phonological demands. One alternative possibility to early processing of phonological information could be a top-down mechanism from regions more directly involved in phonological processing or regions such as the prefrontal cortex (PFC) responsible for implementing task instructions (e.g., “read the presented words aloud”) [Chelazzi et al., 1993; Miller and Cohen, 2001; Wallis et al., 2001]. This scenario cannot be substantiated by the results of this study since no activity was seen within the PFC in the interaction analysis or in the comparisons of reading tasks to fixation. Temporal limitations of fMRI block design studies limit the utility of fMRI in addressing these types of questions, but magnetoencephalography (MEG) can shed more light on this matter. Studies using MEG to investigate pseudoword reading do report early activation in visual and visual association areas, although the nature of the tasks and statistical comparisons do not allow an exact interpretation with regards to the specific region of BA 19 described here [Simos et al., 2002].

CONCLUSIONS

Demands on phonological processing were modulated using a two-by-two design with tasks that had different phonological processing demands with reference to word-type and response-modality. The anterior aspect of the left precentral gyrus (BA 6) and three areas within the left ventral occipitotemporal cortex were found to be active across all reading conditions. The left inferior frontal gyrus and left intraparietal sulcus demonstrated sensitivity to word-type, while bilateral motor, auditory, and extrastriate cortex were modulated by response mode. Activity underlying word reading in BA 19 in the left posterior fusiform cortex demonstrated a word-type by response-modality interaction effect, indicating that phonological processing during reading begins early in the processing stream, at the point at which words are first recognized as alphabetic stimuli.

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