A Positron Emission Tomography Study of Silent and Oral Single Word Reading in Stuttering and Nonstuttering Adults

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Over the last decade positron emission tomography (PET) has been used extensively for the study of language and other cognitive and sensorimotor processes in healthy and diseased individuals. In the present study, $^{15}$O-labeled H$_2$O PET scanning was used to investigate the lateralization and functional distribution of cortical and subcortical activity involved in single word reading in stuttering and non-stuttering individuals. Ten right-handed male stuttering adults and matched nonstuttering individuals were instructed to read individually presented single words either silently or out loud. Subtraction of functional brain images obtained during each of the two reading tasks, and during a non-linguistic baseline task, was used to calculate within-group and between-group differences in regional cerebral blood flow by means of statistical parametric mapping. Increased activation in the left anterior cingulate cortex (ACC) was observed during silent reading in the stuttering speakers but not in the nonstuttering group. Because of the hypothesized role of the ACC in selective attention and covert articulatory practice, it is suggested that the observed increased ACC activation in the stuttering individuals reflects the presence of cognitive anticipatory reactions related to stuttering. During the oral reading task, within-group comparisons showed bilateral cortical and subcortical activation in both the stuttering and the nonstuttering speakers. Between-group comparisons showed a proportionally greater left hemisphere activation in the nonstuttering speakers, and a proportionally greater right hemisphere activation in the stuttering individuals. The results of the present study provide qualified support for the hypothesis that stuttering adults show atypical lateralization of language processes.

KEY WORDS: stuttering, positron emission tomography, word reading, neuroimaging, adults

Ever since the formulation of the Cerebral Dominance Model of stuttering by Travis early this century (Travis, 1934), numerous hypotheses have been formulated concerning the role of the central nervous system in this speech disorder. Clearly, research has failed to find support for Travis’s hypothesis that stuttering resulted from a failure of the central nervous system to establish hemispheric dominance for speech production (Travis, 1934). The idea, however, that stuttering may be associated with atypical brain function has prompted others to pursue this line of research.

As Bloodstein (1995) has pointed out, perhaps the most enduring hypothesis in the literature on neural mechanisms in stuttering is the
presence of atypical lateralization of speech and language functions in stuttering individuals. Over the years, several hypotheses and models of stuttering have been proposed to account for observed lateralization differences between stuttering and nonstuttering speakers. According to one of these models, the Segmental Dysfunction Model (Moore, 1984), stuttering is associated with increased utilization of the right hemisphere for linguistic-motor planning leading to a disruption of the temporal-sequential nature of language during speech production. An alternative hypothesis has been formulated by Webster (Webster, 1997). His Attentional Liability Hypothesis suggests that nonstuttering as well as stuttering speakers rely on left hemisphere processing for speech and language formulation. According to this model, however, stuttering individuals inappropriately and ineffectively engage the right hemisphere during such processing, resulting in interference with the left hemisphere processes, especially those involving the supplementary motor area (SMA). A third hypothesis was formulated by Boberg, Yeudall, Schopflocher, and Bo Lassen, (1983) based on an electrophysiological study of spectral power in the alpha frequency range of neural activation. They interpreted the observation that their stuttering speakers did not show the expected right-greater-than-left alpha relationship in the posterior frontal regions of the brain as suggesting that the stuttering speakers were unable to maintain stable inhibitory control over homologous right hemisphere cortical and subcortical regions during linguistic processing.

Recent advances in functional neuroimaging have allowed researchers to measure subtle changes in regional cerebral blood flow (rCBF) or metabolic rate, providing new tools to investigate the anatomical and functional organization of cortical and subcortical neural processes associated with language (Kertesz, 1994). One technique in particular, positron emission tomography (PET), has been used extensively to map higher order neural activation patterns associated with subcomponents of language formulation (Chertkow & Bub, 1994; Demonet, Fiez, Paulesu, Petersen, & Zatorre, 1996; Petersen, Fox, Posner, Mintun, & Raichle, 1988; Shaywitz et al., 1995).

To date, a small number of investigators have used functional brain imaging methods in an attempt to test the presence of atypical lateralization in stuttering speakers. One of the first rCBF studies of stuttering was done by Wood and Stump (1980). Asymmetrical blood flow during stuttering was observed in Broca's (right > left) and Wernicke's area (left > right). During fluent speech, following administration of haloperidol, a reversal of the blood flow pattern was observed in Broca's area (left > right), but not in Wernicke's area. They interpreted their findings as showing inadequate left cerebral dominance for speech production, but not for speech perception. Unfortunately, the use of medication to increase fluency, and the absence of a control group of normally fluent speakers, make these findings hard to interpret. More recently, Pool, Devous, Freeman, Watson, and Finitz (1991) have used single photon emission computerized tomography (SPECT) to study rCBF changes in stuttering adults during rest (eyes closed). They, too, observed significant blood flow asymmetries in these disfluent speakers. The stuttering speakers showed increased blood flow in the right anterior cingulate area and the left temporal region. In a follow-up investigation, Watson, Pool, Devous, and Freeman (1992) reported a significant correlation between the degree of blood flow asymmetry in the temporal regions and the stuttering speakers' laryngeal reaction times. Flow measures below the group median were associated with increased reaction times. They speculated that the temporal regions may be part of a cortical and subcortical fluency-generating system. In a recent study however, Ingham et al., (1996) failed to find any evidence of brain blood flow differences between a group of stuttering and nonstuttering speakers during rest.

In a number of other functional neuroimaging studies of stuttering, transient changes in brain metabolism or rCBF have been studied while the speakers were completing one or more speech or language tasks. Wu et al. (1995) reported on a PET study using [18F]fluorodeoxyglucose. Four stuttering adults, compared to themselves under a fluency enhancing condition (choral speech) or to a group of normally fluent speakers, showed decreased cerebral activation in a number of unilateral and bilateral regions, including Broca's and Wernicke's region on the left. The observation of decreased activation in the temporal region corroborates Pool et al.'s (1991) observations during rest.

Because of its improved temporal resolution and the opportunity to obtain multiple scans during a single experimental session, most researchers have used the radiotracer [18O]H2O in PET studies of human cognitive and behavioral functions (Wise, Hadar, Howard, & Patterson, 1991). In a study of solo and choral reading in stuttering adults, Fox et al. (1996) reported extensive hyperactivity of the motor system, characterized by a diffuse overactivity of the cerebral and cerebellar motor systems, right lateralization of cerebral motor systems, and an absence or deactivation of temporal lobe activation during choral reading compared to fluent speech in the nonstuttering speakers. Stuttering adults' fluent speech under choral reading resulted in a normalized activation of motor regions, particularly in the supplementary motor area, superior lateral premotor area, and temporal regions. The stuttering speakers continued to show increased right hemisphere lateralization in the primary motor and supplementary motor...
area. Increased right hemisphere lateralization in stuttering adults also was observed by Braun et al. (1997). They compared stuttering and nonstuttering adult males on a variety of simple oral motor tasks and observed left hemisphere lateralization of activation in the nonstuttering speakers, contrasted with primarily right lateralization in the stuttering speakers. During language tasks, the normally fluent adults once again showed lateralized activation of left hemisphere regions, whereas the speakers who stuttered failed to show such lateralization. They speculated that activation of left hemispheric regions may be related to the production of stuttered speech, whereas activation of right hemispheric regions may represent compensatory processes associated with attenuation of stuttering symptoms.

These data generally suggest that stuttering and nonstuttering speakers differ in lateralization of various cortical processes. The observations in the various studies, however, are not easily compared because of significant methodological differences such as the use of medication, choral reading, and the nature of the reading material, among others. It has been shown repeatedly that even subtle variations in task parameters may result in significant changes in the observed neural activation patterns (Démonet, Wise, & Frakowski, 1993; Price et al., 1994; Raichle et al., 1994). More importantly, most functional neuroimaging studies of stuttering have used continuous reading material to elicit speech in the adults. As discussed before, neuroimaging studies of normal speaking individuals typically have used single word production to study language formulation processes. Only a few studies have attempted to investigate more complex language tasks involving sentence formulation (Démonet, Celsis, et al., 1992). As a result, it is very difficult to relate the observations obtained in studies of stuttering to the body of data available for nonstuttering individuals. In addition, the cognitive and sensorimotor complexity of tasks involving continuous speech make it extremely difficult to identify specific speech processes that may account for the observed differences between stuttering and nonstuttering speakers.

The purpose of the present study was to investigate the presence and extent of differences between stuttering and nonstuttering speakers in the lateralization of cortical and subcortical language processes during silent and oral single word reading tasks. Although reading of single words may represent a relatively simple speech task, the extensive body of neuroimaging data that is available on this participant will allow us to interpret differences observed between the speaker groups and between the two experimental tasks with greater functional and anatomic specificity. In addition, the use of a silent reading task will allow us to analyze neural processes in the absence of overt articulation.

**Methods**

**Participants**

Ten stuttering and 10 nonstuttering male adults, ranging in age from 20 to 45 years, participated in this study. All participants were native speakers of English and were screened for a history of relevant neurological or other medical problems and current drug use. The two groups were matched for educational level and for handedness, using the Edinburgh Handedness Inventory (Oldfield, 1971) with a cut-off laterality quotient of 90. The stuttering speakers were selected from the treatment waiting list at the Department of Speech Pathology at the Clarke Institute of Psychiatry. Stuttering was diagnosed by a certified speech-language pathologist based on frequency of within-word disfluencies (>3%) and/or the presence of significant speech-related struggle behavior. None of the stuttering participants had received fluency treatment in the 5 years preceding the present study. Stuttering participant characteristics (age, gender, and handedness), as well as percent intraword disfluencies during spontaneous speech (based on a conversational speech sample of minimum 200 words) and reading (based on the Amplifier Passage, a 286 word long standardized text) are summarized in Table 1. Inter- and intrarater differences for percent disfluent words calculations, based on a random sample of three stuttering speakers, ranged from 0% to 2%. Other than stuttering in the experimental group, none of the participants had a self-reported history of speech, language, or hearing problems. In addition, all the participants were informally screened for the presence of any speech or language problem by a

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Hand</th>
<th>Age</th>
<th>Interview</th>
<th>Oral reading</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>R</td>
<td>33</td>
<td>29</td>
<td>21</td>
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<td>22</td>
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<tr>
<td>5</td>
<td>M</td>
<td>R</td>
<td>29</td>
<td>N/A</td>
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</tr>
<tr>
<td>6</td>
<td>M</td>
<td>R</td>
<td>24</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>R</td>
<td>43</td>
<td>14</td>
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<tr>
<td>10</td>
<td>M</td>
<td>R</td>
<td>24</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

*Due to technical difficulties, the spontaneous speech and oral reading sample obtained during the assessment for this participant were not available for analysis.
qualified speech-language pathologist at the time of initial fluency assessment.

**Language Tasks**

**Preliminary Study: Word Stimulus Selection**

A preliminary study was done in which a list of 576 multisyllabic words was presented to a group of 18 university undergraduate students and 26 stuttering adults who participated in a treatment refresher program at the Clarke Institute of Psychiatry. Participants were asked to rate each individual word on a 5-point scale ranging from 1, *it is very easy for me to see a specific image almost immediately*, to 5, *it is almost impossible for me to see an image of this word*. The words used as stimuli in the silent and oral reading tasks (see below) in the present study all obtained a mean rating of low imagery (4 or 5). Low-imagery words were selected because previous research on nonstuttering speakers has shown that their processing involves primarily left hemisphere functions, but high-imagery words show increased right hemisphere activation (Fletcher et al., 1996). Because the primary goal of this study was to investigate the presence of brain laterality differences between stuttering and nonstuttering adults, it was decided to restrict item selection to low-imagery words to avoid any artificial obscuring of a potential right hemisphere effect in the stuttering speakers.

**Main Study: Baseline and Experimental Tasks**

Participants were asked to perform three tasks during the experiment: a non-linguistic baseline task and two language tasks, silent and oral reading. Each reading task was presented twice, using similar but different words, resulting in a total of four reading tasks per participant. In addition to the four reading tasks, the participants also completed a baseline task twice. This baseline task was always the first and last task in the experimental session. The order of the reading tasks was counterbalanced across participants (silent-oral-silent-oral for half of the participants within each group, and oral-silent-oral-silent for the other half). The stimuli for the baseline and reading tasks were presented on a computer monitor positioned at a comfortable reading level for each participant. At the beginning of the scanning session, each participant was given a short practice using 10 stimuli for each task similar to the ones used during the actual experiment.

**Baseline Task.** During the baseline task, participants viewed individual strings of Xs varying randomly in length, similar to the words used in the silent and oral reading tasks. The baseline task was selected to allow measurement of brain activation resulting from visual stimulation without associated phonological or semantic processes. A total of 25 individual character strings were presented for 2 seconds each, with an interstimulus interval randomly ranging from 1.5 seconds to 2.0 seconds. Presentations of individual character strings were separated by a single X located in the middle of the monitor screen.

**Silent Reading Task.** In the silent reading task, 25 three-syllable words were presented to the participants, with the instruction to read each of the words mentally. Participants were instructed specifically to avoid overt articulation. Similar to the baseline task, words were presented individually for 2 seconds each, with an interstimulus interval ranging randomly from 1.5 seconds to 2.0 seconds for a total duration of approximately 85 seconds per word list.

**Oral Reading Task.** During the oral reading task, a list of 25 words, equivalent to those used for silent reading, was presented to the participants in a manner similar to the silent reading task. Participants were instructed to read the words out loud at a normal loudness level. To avoid the introduction of time pressure during reading, especially for the stuttering speakers, all participants were instructed to complete each word prior to attempting the say the next one. If the production of a word overlapped with the presentation of the next one, participants were instructed to ignore the new word, finish saying the previous word, and wait for the presentation of the next word. Because the purpose of the present study was to investigate brain activation patterns associated with natural speech, no effort was made to control or minimize the presence of stuttering in the experimental group. Each participant’s oral production was recorded on audiotape using a lapel microphone positioned approximately 20 centimeters from the mouth.

**Positron Emission Tomography Scanning**

Positron emission tomography scans were obtained using a GEMS-Scanditronix PC 2048-15B head scanner at the PET Centre of the Clarke Institute of Psychiatry. Participants were scanned in a supine position with a custom-fitted thermoplastic mask for head stabilization, which does not interfere with speech movements. Emission scans were done using 1110 MBq (30mCi) of $^{15}$O$^2$H$_2$O injected as a bolus into a forearm vein at the beginning of each task. Scans were acquired for 60 seconds, with individual scans separated by an 11-minute interval. Word stimulus presentation for each of the control or reading tasks was started at the time of the injection, and 60-second scans were acquired during each task starting approximately 20 seconds following...
injection. Each control or reading task ended within 10 seconds after completion of the 1-minute scan.

PET scans were reconstructed using a Hanning filter and attenuation correction. To avoid arterial blood sampling during the scanning to determine absolute blood flow, which would make the experiment more invasive, integrated regional counts were used as an index of regional cerebral blood flow. Because arterial blood sampling data was not obtained in the present study, increased or decreased activation levels in the scans obtained do not necessarily imply that the absolute blood flow in the affected cortical or subcortical regions also is increased or decreased. Rather, an increase or decrease in regional activation should be interpreted with reference to the conditions used in the subtraction comparison under investigation.

**Data Analysis**

PET scans were analyzed using Statistical Parametric Mapping (SPM; Wellcome Department of Cognitive Neurology, 1996). Between- and within-subject variations in global blood flow across the scans were removed using analysis of covariance with global activity as covariate on a pixel-by-pixel basis (Friston, Frith, Liddle, & Frackowiak, 1991). Statistical Parametric Mapping analysis involved the following steps: (1) three-dimensional stereotactic reorientation of the images along the Anterior Commissure–Posterior Commissure (AC/PC) line, (2) plastic transformation of these images using a nonlinear resampling technique to minimize for anatomical variance across participants, and (3) spatial filtering to enhance the signal in the presence of the noise introduced by anatomical and functional heterogeneity across participants (Frackowiak, Friston, Frith, Dolan, & Mazzotta, 1997). All data were smoothed using a 15-mm filter in the x, y, and z directions, resulting in final image resolution (full width of half maximum) $x = 13.2$ mm, $y = 14.6$ mm, $z = 18.5$ mm.

The scans of different tasks were compared with each other on a pixel by pixel basis. The statistical significance of each difference was assessed by comparing the magnitude of the difference at a pixel with the error variance at that particular pixel. The resulting map of the $Z$ statistic at each pixel constitutes the SPM (Friston et al., 1991). Type I errors were minimized by evaluating only those pixels where the $Z$ statistic exceeds a threshold that has been adjusted for the number of resolvable elements in the image. This is effectively the same as controlling for multiple comparisons, but uses the inherent spatial resolution of the processed PET images to make the correction (Frackowiak et al., 1997). For the within-group comparison, pixels were considered statistically significant, corrected for multiple comparisons, if they reached a minimum $Z$ value of 3.09 (corrected $p \leq 0.05$) (Friston et al., 1991). A minimum $Z$ value of 2.33 was used for interaction analyses due to their lower statistical sensitivity (Frackowiak et al., 1997, Grasby et al., 1993). Regions of activation were referenced relative to Talaraich and Tournoux brain coordinates (Talairach & Tournoux, 1988).

**Results**

**Silent Reading**

Cortical and subcortical regions of increased neural activation, associated specifically with silent reading within each of the two groups, were identified by subtracting the activation pattern obtained during the baseline condition from that observed during silent reading. For the between-group comparisons, increased activation patterns for the target group (either stuttering or nonstuttering speakers) were obtained by subtracting the silent minus baseline image in the non-target group from the silent minus baseline image obtained for the target group.

**Within-Group Effects**

Nonstuttering Speakers. Identified areas of significantly increased activation ($Z \geq 3.09$) during silent reading in the control speakers are shown in Table 2, including the stereotaxic coordinates of observed activation peaks (Talairach & Tournoux, 1988) and graphically in Figure 1. The $x$, $y$, $z$ Talairach & Tournoux coordinates in the Tables localize the pixel with peak activation in a continuous cluster of significantly activated pixels. In the present analysis, such clusters can range from 20 pixels to many hundreds or even thousands of pixels in size. As a result, it is important to interpret the peak activation coordinates in each table in conjunction with the SPM images in the corresponding figures to determine the localization and extent of the region of activation identified by the coordinates.

A large area of activation could be observed bilaterally in the cerebellum (but left > right) extending into the primary occipital region (Brodmann Area [BA] 18). Additional activation was observed bilaterally in the precentral motor cortex at the level of the insula. Some increased activation also was observed in the left medial frontal gyrus (BA 9).

Stuttering Speakers. Table 2 and Figure 1 show the regions of increased activation ($Z \geq 3.09$) observed in the stuttering speakers during silent reading compared to the baseline condition. As in the normal speaking speakers, significantly increased neural activation was observed bilaterally in the cerebellar and lingual gyrus (BA 17). Additional activation could be observed in the left inferior frontal gyrus (BA 45), in the region of Broca's area.
Table 2. Silent reading versus baseline: Localization of suprathreshold peak activation (anatomical region and x, y, and z coordinates), with associated Z values, in the within- and between-group comparisons for the stuttering (S) and nonstuttering speakers (NS).

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>Region</th>
<th>Z value</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Talairach &amp; Tournoux (1988)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within-group (NS)</td>
<td>L Cerebellum</td>
<td>4.70</td>
<td>-36</td>
<td>-80</td>
<td>-20</td>
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</tr>
<tr>
<td></td>
<td>L Cerebellum</td>
<td>4.31</td>
<td>-8</td>
<td>-92</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R Insula</td>
<td>4.11</td>
<td>38</td>
<td>14</td>
<td>4</td>
<td></td>
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<tr>
<td></td>
<td>L Medial frontal gyrus</td>
<td>3.60</td>
<td>-10</td>
<td>46</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L Precentral gyrus</td>
<td>3.57</td>
<td>-44</td>
<td>10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Within-group (S)</td>
<td>L Anterior cingulate gyrus</td>
<td>4.85</td>
<td>-12</td>
<td>26</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L Lingual gyrus</td>
<td>4.00</td>
<td>-18</td>
<td>-98</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R Cerebellum</td>
<td>3.68</td>
<td>4</td>
<td>-74</td>
<td>-20</td>
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<tr>
<td></td>
<td>L Inferior frontal gyrus</td>
<td>3.56</td>
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<tr>
<td></td>
<td>L Cerebellum</td>
<td>3.46</td>
<td>-16</td>
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<tr>
<td>Between-group (NS)</td>
<td>L Middle occipital gyrus</td>
<td>3.22</td>
<td>-32</td>
<td>-90</td>
<td>16</td>
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<tr>
<td></td>
<td>R Precentral gyrus</td>
<td>3.10</td>
<td>44</td>
<td>10</td>
<td>8</td>
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</tr>
<tr>
<td></td>
<td>L Lingual gyrus</td>
<td>3.10</td>
<td>-4</td>
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<tr>
<td></td>
<td>L Cerebellum</td>
<td>3.09</td>
<td>-34</td>
<td>-82</td>
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<td></td>
<td>L Cuneus</td>
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<tr>
<td></td>
<td>R Cerebellum</td>
<td>2.78</td>
<td>10</td>
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</table>

A notable difference between the scans of the stuttering and the nonstuttering group was the large area of increased activation in the left cingulate cortex (BA 24/32) in the stuttering speakers. The localization of peak activation (12 mm from midline) suggests involvement of sulcal cortex in addition to medial wall cortex.

**Interaction Effects**

To obtain a more direct comparison of neural activation patterns in stuttering and nonstuttering speakers, the interaction effect between participant groups (stuttering versus nonstuttering) and scanning conditions (silent reading versus baseline) was analyzed statistically ($Z \geq 2.33$; Table 2 and Figure 2). Cortical areas of increased activation in the nonstuttering speakers relative to the stuttering controls were observed in the right precentral cortex, extending into insular cortex, the left occipital cortex at the level of the middle occipital, and lingual gyrus [BAs 18 and 19], and bilaterally in the cerebellum. For the stuttering speakers, no between-group activation differences reached the specified $Z$ threshold level of 2.33.

**Oral Reading**

Cortical and subcortical regions of increased neural activation, associated specifically with oral reading within each of the two groups, were identified by subtracting the activation pattern obtained during the silent reading condition from that observed during oral reading. For the between-group comparisons, increased activation patterns for the target group (either stuttering or nonstuttering speakers) were obtained by subtracting the oral minus silent image in the non-target group from the oral minus silent image obtained for the target group.

No effort was made to control the presence or absence of stuttering during the oral reading tasks. As a result, stuttering speakers showed varying degrees of disfluencies during each of the two single-word reading tasks. The mean stuttering frequency (in percentage) was 30.8 (standard deviation: 35.2, range 0–100) and 25.6 (standard deviation: 32.6, range 0–100), in the first and second readings, respectively.

**Within-Group Effects**

Nonstuttering Speakers. Cortical and subcortical regions that showed significantly increased activation ($Z \geq 3.09$) in the nonstuttering speakers during oral reading are shown in Table 3 and Figure 3. A large region of increased activation was observed in the left hemisphere. Although only one peak was identified in this region (left superior temporal gyrus [BA 42] – see Table 3), Figure 3 reveals that this region actually stretches from the frontal primary motor cortex to the temporal cortex posteriorly. Similarly, significant activation was observed in the right hemisphere. Table 3 shows a peak activation in the right postcentral gyrus (BA 43), but Figure 3 again reveals an extensive activation ranging from primary motor to temporal cortex. Additional activation could be...
observed in the right inferior frontal gyrus (BA 47) and bilaterally in the cerebellum.

Stuttering Speakers. Regions of increased neural activation ($Z \geq 3.09$) during oral reading in the stuttering speakers are shown in Table 3 and Figure 3. It is obvious in Figure 3 that, despite the fact that only four main activation peaks were identified during SPM analysis (see Table 3), the stuttering speakers showed widespread cortical and subcortical activation during the oral reading task. In the left hemisphere, a large region could be identified which stretched from the precentral motor cortex (BA 4/6) posteriorly to the superior temporal gyrus (BA 22). This cortical activation showed a largely bilateral pattern as increased activation was
Figure 2. Statistical parametric maps of between-group comparisons (nonstuttering versus stuttering adults) for increases in regional cerebral blood flow during silent reading relative to baseline.

Table 3. Oral versus silent reading: localization of suprathreshold peak activation (anatomical region and x, y, and z coordinates), with associated Z-values, in the within- and between-group comparisons for the stuttering (S) and nonstuttering speakers (NS)

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>Region</th>
<th>Z value</th>
<th>Talairach &amp; Tournoux (1988)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td>Within-group (NS)</td>
<td>L Superior temporal gyrus</td>
<td>5.25</td>
<td>-58</td>
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<tr>
<td></td>
<td>R Postcentral gyrus</td>
<td>5.05</td>
<td>58</td>
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<tr>
<td></td>
<td>L Cerebellum</td>
<td>4.63</td>
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</tr>
<tr>
<td></td>
<td>R Inferior frontal gyrus</td>
<td>3.90</td>
<td>48</td>
</tr>
<tr>
<td>Within-group (S)</td>
<td>L Cerebellum</td>
<td>6.55</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>R Superior temporal gyrus</td>
<td>6.28</td>
<td>60</td>
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<tr>
<td></td>
<td>L Anterior cingulate gyrus</td>
<td>3.88</td>
<td>-8</td>
</tr>
<tr>
<td></td>
<td>L Medial frontal gyrus</td>
<td>3.72</td>
<td>-4</td>
</tr>
<tr>
<td>Between-group (NS-S)</td>
<td>R Middle occipital gyrus</td>
<td>3.08</td>
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<tr>
<td></td>
<td>Subcortical</td>
<td>3.07</td>
<td>-32</td>
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<tr>
<td></td>
<td>L Posterior Cingulate gyrus</td>
<td>2.88</td>
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<tr>
<td></td>
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<td>2.80</td>
<td>-58</td>
</tr>
<tr>
<td></td>
<td>L Inferior frontal gyrus</td>
<td>2.62</td>
<td>-36</td>
</tr>
<tr>
<td></td>
<td>L Orbital gyrus</td>
<td>2.58</td>
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</tr>
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<td>Between-group (S-NS)</td>
<td>R Precentral gyrus/Insula</td>
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<td>38</td>
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<td></td>
<td>L Cuneus</td>
<td>3.26</td>
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<tr>
<td></td>
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<td>3.21</td>
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<td></td>
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<td>2.58</td>
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observed in homologous areas in the right hemisphere. As can be seen in Table 3, the most intense activation peak in this cluster was observed in the right hemisphere. Additional regions of increased activation observed bilaterally in the anterior cingulate cortex (with the main peak in the left hemisphere), the left medial frontal gyrus at the level of the supplementary motor area, and bilaterally in the cerebellum.

**Interaction Effects**

To obtain a more direct comparison of neural activation patterns in stuttering and nonstuttering speakers, the interaction effect between participant group (stuttering versus nonstuttering) and scanning condition (oral reading versus silent reading) was analyzed statistically ($Z \geq 2.33$).
Table 3 and Figure 4 show the regions of greater activation during oral reading in the nonstuttering speakers relative to the stuttering speakers. Figure 4 reveals a clear left hemisphere effect, except for some bilateral activation in the occipital cortex (BA 19). Unilateral greater left hemisphere activation was observed frontally at the level of the inferior frontal (BA 45) and the superior temporal gyrus (BA 42). Additional regions of greater left activation included the posterior cingulate gyrus (BA 31), and a subcortical area in the region of the thalamus.

A very different activation pattern was observed in the stuttering speakers (Table 3 and Figure 4). As can be seen in Figure 4, cortical regions of increased activation during oral reading in the stuttering speakers were
localized predominantly in the right hemisphere, including a large area of activation in the insula, extending into the precentral gyrus (BA 6) and the homologous of Broca's area (BA 44) and the middle frontal gyrus (BA 9 and 46). Greater right hemisphere activation was observed also in the supramarginal gyrus (BA 40). Increased left hemisphere activation was observed in the parieto-occipital region (cuneus, BA 17 and 19) and the precentral gyrus (BA 6). Subcortically, bilateral activation could be observed at the level of the thalamus, and increased right hemisphere activation was apparent in the cerebellum.

Discussion

The primary purpose of this study was to investigate the presence of differences in lateralization of cortical and subcortical processes involved in single word processes in stuttering and nonstuttering adults. The main observations for silent reading can be summarized as follows: (1) Both the stuttering and the nonstuttering speakers showed significant activation of left cortical motor areas. For the nonstuttering speakers increased activation was observed more posteriorly in the primary motor cortex and insula, with stuttering speakers showing greater activation more frontally in Broca's area. (2) Both stuttering and nonstuttering speakers showed significant levels of activation in the cerebellum and occipital region. (3) The stuttering, but not the nonstuttering speakers showed significantly increased activation in the left anterior cingulate cortex. (4) Interaction analysis of the stuttering and nonstuttering speakers, comparing silent reading versus rest conditions, showed relatively greater precentral and insular cortex activation in the right hemisphere activation for the nonstuttering speakers.

For oral reading, the main observations were (1) Both the stuttering and the nonstuttering speakers showed significantly increased bilateral activation in the motor and temporal cortex compared to silent reading, and (2) interaction analysis of the stuttering and nonstuttering speakers, comparing oral versus silent reading, revealed proportional greater left hemisphere activation in the nonstuttering individuals, with the stuttering speakers showing proportionally increased activation lateralized to the right.

Based on the present findings, it can be concluded that observed differences between stuttering and nonstuttering individuals in the lateralization of neural processes involved in single word reading are task dependent. For the silent reading task, no evidence for increased right hemisphere lateralization in the stuttering speakers was found. Oral reading, on the other hand, showed clear evidence of a relative greater reliance on right hemisphere neural activation in the stuttering speakers. In the remainder of the discussion, we will address these and other observations arising from the present study in greater detail.

Left Motor Cortex Activation During Silent Reading

The present PET data on silent word reading did not provide unequivocal support for the hypothesis that stuttering speakers relied more on right hemisphere processes. Both the stuttering and the nonstuttering speakers showed a pattern of increased left hemisphere activation that included the occipital and frontal motor cortex, confirming previous studies of word reading (Petersen et al., 1988; Pugh et al., 1996).

The nonstuttering and stuttering speakers differed in which area of the frontal motor cortex was activation. The nonstuttering speakers revealed higher activation in primary motor cortical areas and insula. The stuttering speakers showed increased activation more frontally in a region corresponding to Broca's area. Activation in the left prefrontal cortex, including Broca's area, has been consistently associated with silent verbal tasks that involve memory retrieval and silent articulation (Fletcher, Shallice, Friston, Frackowiak, & Dolan, 1996, Grasby et al., 1993, Warburton et al., 1996). Furthermore, activation in this area has been found to be associated with simultaneous activation in the anterior cingulate cortex suggesting increased attentional load during these tasks (Grasby et al., 1993). The simultaneous activation of Broca's area and the anterior cingulate cortex observed in the stuttering speakers may suggest that they were actively involved in mental rehearsal of the articulatory pattern of the words even though no overt production was required during reading. In comparison, the lack of prefrontal motor cortex and anterior cingulate activation in the nonstuttering speakers may suggest that, although some associated motor activation may have taken place during silent reading (as suggested by the increased precentral cortex activation), they were less intensely engaged in silent rehearsal of the words presented.

Increased Anterior Cingulate Activation in the Stuttering Speakers

The anterior portion of the cingulate cortex (ACC) has an important role in emotion, attention, and working memory (Devinsky, Morrell, & Vogt, 1995; Dum & Strick, 1993; Murtha, Chertkow, Beauregard, Dixon, & Evans, 1996). It has extensive neural connections with the amygdala, periaqueductal grey and autonomic brainstem nuclei, but also with motor systems, including
primary motor cortex and striatum (Devinsky et al., 1995; Dum & Strick, 1993). Regions of the ACC that project to the limbic system and the thalamus tend to be located on the gyral surface of the cortex. Motor regions are largely found in the sulcal region of the cortex.

One interpretation of the observed increased ACC activation in the stuttering speakers during silent reading is based on the hypothesized role of the ACC in selectively focusing attention on task-related targets with high functional significance (Pardo, Pardo, Janer, & Raichle, 1990; Posner & Petersen, 1990). Because stuttering individuals often report anticipatory scanning during reading, behavior that is not unlike scanning for targets in other experiments, it seems reasonable to assume that the stuttering speakers when reading silently may have been actively engaged in scanning for words that have the potential for stuttering if read out loud. Such anticipatory word scanning would not be expected in the nonstuttering individuals.

An alternative, but possibly related, interpretation of the increased ACC activation in the stuttering participant group is that it reflects covert articulatory practice during silent reading. Paus, Petrides, Evans, and Meyer (1993) observed increased activation of a speech-related region in the ACC during manual and oculomotor tasks, which required no overt speech output but which triggered covert speech, especially during the more difficult components of these tasks. Therefore, our observation of increased ACC activation in the stuttering but not the nonstuttering speakers may indicate group differences in the presence of covert articulation during the silent reading task. The fact that peak activation was found in the sulcal region of the ACC, which has extensive neural connections to the lateral motor regions (Dum & Strick, 1993), lends some support for this interpretation.

Although both aforementioned explanations of the increased ACC activation in the stuttering speakers seem plausible, it cannot be excluded that the activation in this region is related to general experimental conditions, such as receiving instructions, preparation, and anticipation of the task, rather than any task-related processing itself (Murtha et al., 1996). In this case, increased ACC activation in the stuttering, but not the nonstuttering, speakers could reflect between-group differences in general task anticipation, rather than specific word scanning or covert articulation processes. The fact that significant anterior cingulate activation differences between the two groups were observed in the within-group comparisons and not the interaction analysis suggests that this observed between-group difference is quantitative rather than qualitative in nature.

Higher Right Hemisphere Activation in Nonstuttering Speakers During Silent Reading

The proportionally higher right hemisphere activation during silent reading in the nonstuttering speakers compared to the stuttering speakers was an unexpected finding. Indeed, this observation is contrary to any other finding on language processing in normal speaking individuals reported in the literature. A comparison of the within-group subtraction images for silent reading revealed, however, that the nonstuttering speakers showed increased bilateral activation in the right frontal cortex. The absence of such activation in the stuttering speakers suggests that the observed right hemisphere activation in the between-group comparison may not have been due to significantly increased activation in the nonstuttering speakers, but rather may have resulted from cortical deactivation in the stuttering speaker group. This, indeed, is what was found when the adjusted average regional blood flow levels were inspected for the stuttering and nonstuttering speakers in each experimental condition. For each of the identified clusters of right hemisphere activation in Figure 1, the nonstuttering speakers showed activation levels similar to or slightly above baseline condition. The stuttering speakers, on the other hand, showed decreased blood flow levels in these regions. This finding indicates that the observed significant right hemisphere interaction effect resulted from cortical deactivation in the stuttering speakers, rather than from increased activation in the nonstuttering control group. An intriguing finding was that, in contrast to the deactivation of right hemisphere regions in the stuttering speakers, the relatively higher activation in left precentral cortex in the nonstuttering speakers (Figure 1) was due to increased blood flow in the control group. Indeed, the adjusted flow measures for the stuttering speakers for this region did not differ observably from baseline. As a consequence, the significant differences in activated cortical regions observed between the two groups during silent reading can not be explained by a general decrease in cerebral blood flow in the stuttering speakers. Rather it appears to represent a selective deactivation of right hemisphere cortical regions in this group.

Oral Reading: Between-Group Differences in Lateralization

Activation differences in neural activation pattern were observed between the stuttering and the nonstuttering speakers during oral reading relative to silent reading. These between-group differences were most obvious in the interaction analysis. As expected, the
nonstuttering speakers showed increased activation almost exclusively in the left hemisphere. The notable exception to this was the occipital region where oral reading was associated with bilateral activation in the visual cortex. Undoubtedly, this was due to the increased demands associated with the processing of the visual linguistic stimuli. In addition, significantly increased activation was observed in the left posterior cingulate cortex, an area found to be involved in memory and visually imagery (Fletcher et al., 1996).

As would be expected during an oral reading task, increased activation was observed in left hemisphere areas generally associated with oral speech, including Broca’s area and temporal cortex. It has been suggested in a number of recent PET studies that the activation in the superior temporal gyrus may be related closely to the auditory perception of the acoustic signal during oral speech production (Price et al., 1996).

A very different activation pattern was found for the stuttering speakers. In this group, increased neural activation in the interaction analysis was largely confined to the right hemisphere, with exception of the cuneus region in the occipital cortex, which showed a left hemisphere activation. This latter area has been shown to be involved in visual mental imagery (Platel et al., 1997), not unlike the left posterior cingulate which was found to be more highly activated in the nonstuttering speakers. In the right hemisphere, the stuttering speakers showed increased activation in the frontal motor cortex, in an area stretching from the primary motor cortex and insula frontally to Brodmann Areas 9 and 46. Brodmann Area 9, which is part of the frontal association cortex, is known to have a role in motor planning (Kuppermann, 1991). Part of BA 46 on the right constitutes the homologous of Broca’s area, a region known to be importantly involved in speech as well as non-speech movements (Blumstein, 1995). Bilateral motor activation was observed only in the precentral gyrus (Brodmann Area 4/6), with peak activation located ventrally, which suggests that neural activation was more pronounced in an area of the motor cortex involved in oral motor control. In addition, increased activation was observed in the right supramarginal cortex. The supramarginal gyrus is hypothesized to play an important role during phonological encoding of language (Frackowiak et al., 1997). These results suggest that, although both groups showed bilateral activation in primary motor cortex associated with overt articulation, the stuttering speakers may have relied proportionally more on right hemisphere processing resources for the cognitive formulation and planning of word production.

It is important to note that the within-group comparison for the stuttering as well as the nonstuttering speakers showed widespread bilateral activation in precentral and postcentral cortex during oral reading. As such, the current data do not suggest that neural activation in the stuttering speakers was exclusively localized in the right hemisphere during oral reading, but rather that they engaged comparatively more right hemisphere processes than did the nonstuttering control speakers. Indeed, analysis of the adjusted average regional blood flow levels showed that the greater left hemisphere activation in the nonstuttering speakers and the greater right hemisphere activation in the stuttering speakers was due to proportionally increased activation in each of the two speaker groups, rather than selective regional deactivation as was the case in the silent reading condition.

To the extent that the right hemisphere can be considered to be less effective in processing linguistic material, the findings in the oral reading task appear to provide support for the Segmental Dysfunction Hypothesis proposed by Moore (1984). A more recent model of the neural basis of fluency has been presented by Watson and Freeman (1997). These authors differentiated between a cognitive, linguistic, and speech motor component in the production of fluency. Stuttering, then, can result from a breakdown in the integrity of, and coordination between, these different components. If the stuttering adults indeed are found to use less efficient processing resources for the production of speech, the present data suggests that such a breakdown may occur at the level of any of these components separately or simultaneously. Further research will need to (1) attempt to isolate each of these components to identify the nature and extent of their involvement in a “fluent speech generating system” (Watson & Freeman, p. 158) and (2) investigate the interrelationships between the various components for the generation of fluent speech.

In the present study, no effort was made to control the level of speech fluency in the speakers during the oral reading task. This was done purposively to investigate neural processes underlying the habitual speech pattern in the adults, rather than introducing an external fluency-enhancing condition. As a result, the right hemisphere activation observed in the stuttering speakers may reflect an inherent neural organization of speech and language processes independent of the level of speech fluency or, alternatively, may be a consequence of the presence of stuttering. Because fluency was not manipulated in the current study, the available data can not answer this question. Preliminary data from our laboratory which have shown a persistent right hemisphere bias in five adults who had gained a high level of speech fluency immediately following an intensive treatment program, however, suggest that the right hemisphere processing may be independent of the level of speech fluency (Kroll, De Nil, Kapur, & Houle, 1997). Reports by other researchers of increased left
hemisphere processing following the introduction of fluency enhancing conditions (Fox et al., 1996, Wu et al., 1995) point to the need for more research in this area.

**Conclusion**

Silent reading in the stuttering adults was characterized by significant activation of the left anterior cingulate region as well as activation in the left inferior prefrontal motor cortex. It is suggested that this activation reflects increased anticipatory scanning and/or covert articulation processes in the stuttering adults. There was no evidence in our data that the stuttering speakers during silent reading relied proportionally more on right hemisphere processes. Our data, however, did provide support for the hypothesis that stuttering individuals show proportionally increased right hemisphere activation during oral speech compared to the nonstuttering speakers. The reason for the discrepancy in activation pattern between the silent and the oral reading condition is not clear. It is possible that the silent and oral reading tasks used in the present study may differ in terms of their underlying demands on neural computational processes. More specifically, the processing demands involved in passive single-word reading task may not have been high enough to reveal significantly increased right hemisphere neural processing in the stuttering speakers. Indeed, silent reading tasks that require more active lexical processing, such as semantic or phonological categorization tasks, typically have resulted in more widespread cortical activation in normal speaking individuals, compared to passive reading tasks similar to those used in the present study (Démonet, Chollet, et al., 1992; Démonet et al., 1993; Liotti, Gay, & Fox, 1994). Alternatively, it remains possible that the increased right hemisphere activation during the oral reading task was related directly to the presence of stuttered speech. If so, the absence of stuttering during the silent reading task would account for the lack of right hemisphere activation in this condition. The limitations in temporal resolution inherent in PET scanning precluded the differentiation between activation associated with fluent and stuttered words in our study. Such differentiation is needed in our efforts to investigate the potential role, if any, of right hemisphere activation in causing or maintaining stuttering. Studies currently underway in our laboratory, using both PET and fMRI techniques, will address these and other issues identified in the present paper.

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**References**


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