



Common features of fluency-evoking conditions studied in stuttering subjects and controls: an H₂¹⁵O PET study

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Abstract

We used H₂¹⁵O PET to characterize the common features of two successful but markedly different fluency-evoking conditions — paced speech and singing — in order to identify brain mechanisms that enable fluent speech in people who stutter. To do so, we compared responses under fluency-evoking conditions with responses elicited by tasks that typically elicit dysfluent speech (quantifying the degree of stuttering and using this measure as a confounding covariate in our analyses). We evaluated task-related activations in both stuttering subjects and age- and gender-matched controls.

Areas that were either uniquely activated during fluency-evoking conditions, or in which the magnitude of activation was significantly greater during fluency-evoking than dysfluency-evoking tasks included auditory association areas that process speech and voice and motor regions related to control of the larynx and oral articulators. This suggests that a common fluency-evoking mechanism might relate to more effective coupling of auditory and motor systems — that is, more efficient self-monitoring, allowing motor areas to more effectively modify speech.

These effects were seen in both PWS and controls, suggesting that they are due to the sensorimotor or cognitive demands of the fluency-evoking tasks themselves. While responses seen in both groups were bilateral, however, the fluency-evoking tasks elicited more robust activation of auditory and motor regions within the left hemisphere of stuttering subjects, suggesting a role for the left hemisphere in compensatory processes that enable fluency.

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Educational objectives: The reader will learn about and be able to: (1) compare brain activation patterns under fluency- and dysfluency-evoking conditions in stuttering and control subjects; (2) appraise the common features, both central and peripheral, of fluency-evoking conditions; and (3) discuss ways in which neuroimaging methods can be used to understand the pathophysiology of stuttering.

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Two of the most effective fluency-evoking conditions, demonstrating at least a 90% reduction in stuttering, are singing and pacing speech with a metronome (Andrews, Howie, Dozsa, & Guitar, 1982). Because of their similar effectiveness, it has been suggested that, in spite of marked differences in their surface features, some common mechanism might explain their ability to improve fluency. However, to date, no studies have directly compared these conditions. Searching for commonalities between them provides another approach for determining what might be at the core of dysfluency, and how pathophysiological mechanisms might be altered to enable fluent speech.

Several possible explanations have been considered for how these maneuvers might improve fluency. One mechanism that might lead to fluency enhancement under both conditions is modulation of auditory feedback. Webster and Lubker (1968) proposed that speaking under metronomic pacing or singing might: either modify the interrelationship between motor activity and auditory feedback; establish a temporal relationship between external cues and speech or voice production; or modify the air versus bone-conducted auditory signal. Previous studies have investigated both peripheral and central auditory mechanisms in PWS (e.g., Blood, 1985; Blood & Blood, 1986; Hall & Jerger, 1978; Hannley & Dorman, 1982; Samelin et al., 1998; Stager, 1990; Toscher & Rupp, 1978). However, the measures of auditory function studied thus far have never been correlated with degree of fluency change under these fluency-evoking conditions.

From a production standpoint, several studies have compared speech-related variables that are altered under fluency-evoking conditions to determine if the degree of change correlates with the degree of fluency improvement. Under metronome pacing, the following have been reported: slower speech rate (Ingham & Andrews, 1973); decreases in peak pressure and flow for plosive sounds (Adams, Runyan, & Mallard, 1975; Hutchinson & Navarre, 1977; Stager, Denman, & Ludlow, 1997); decreases in vocal intensity of vowel sounds (Stager et al., 1997); decreases in the variability of duration of both voiced and voiceless segments (Janssen & Wieneke, 1987); variable timing of successive syllables (Boutsen, Brutten, & Watts, 2000); and increases in vowel duration and/or phonation time (Brayton & Conture, 1978). However, improvements in fluency have been found with faster rates under metronome pacing (Hanna & Morris, 1977) and without changes in vowel intensity (Brayton & Conture, 1978), suggesting that these speech production changes were associated with, but did not necessarily cause

the improvement in fluency. With singing, an increase in word or voicing duration in the absence of increased vocal SPL has been reported (Colcord & Adams, 1979). Based on these studies, a single mechanism, increased phonation or vowel durations could explain improved fluency in both conditions. On the surface, this explanation has some validity because the manipulation of phonation duration had been demonstrated as being an effective therapeutic intervention (e.g., Ingham, Montgomery, & Ulliana, 1983). In the present study, we measured changes in phonation time to see if this peripheral mechanism might represent a shared feature of the fluency-evoking conditions.

However, since fluency may also be enhanced by centrally mediated changes in speech production, auditory or other sensory feedback, or by a combination of these, we used H₂¹⁵O positron emission tomography (PET) to evaluate these possibilities, paying close attention to changes in activation of cortical auditory association areas, and in activation of cortical and subcortical motor regions.

To date, several studies have used this method to study controls and PWS under both fluency- and dysfluency-evoking conditions (Fox et al., 1996, 2000; Wu et al., 1995). A task commonly used to elicit stuttering is reading, with choral reading used as a fluency-evoking task. In most of these studies, significant activations or deactivations during tasks that produced dysfluent speech were used to characterize the neural correlates of stuttering. In the present study, the goal was instead to characterize features of the fluency-evoking conditions themselves, using more than one of these conditions to identify the features they had in common.

A previous study from this laboratory utilized two different fluency-evoking conditions (Braun et al., 1997). However, in that study, images from the fluency-evoking tasks were averaged before baseline scans were subtracted; fluency-evoking conditions were not compared directly. In addition, contrasts between fluency- and dysfluency-evoking tasks did not control for stuttering that occurred in the latter condition (indeed, we were interested in highlighting activity related to stuttered speech). Furthermore, baseline images in that study were not acquired at rest, but rather were from a task in which the subjects produced oral-motor movements similar to speech. By using such a task as baseline, the features related speech production that might be shared by the fluency-evoking tasks were factored out.

The purpose of the present study was to use PET to identify common or shared areas of activation, as well as differences in levels of activation, associated with paced speech and singing, comparing these conditions with dysfluency-evoking speech tasks in PWS and control subjects. The principal baseline for these contrasts was rest rather than an oral-motor task that simulated speech. Areas of activation were compared between PWS and controls so that mechanisms related to the tasks themselves (activations present in both groups) could be differentiated from idiosyncratic effects the tasks might have in the brains of stuttering subjects. Measures of dysfluency, acquired during the PET scans themselves, were used as covariates in these contrasts in order to minimize the effects of stuttering *per se*, highlighting the features of the tasks themselves. It was our goal to use these findings to generate hypotheses that can be tested using other fluency-evoking techniques.

1. Methodology

1.1. Subjects

The subjects included 17 adults with persistent developmental stuttering, 7 females (23–46 years of age) and 10 males (23–50 years). Controls were 17 adults, 8 females (24–50 years) and 9 males (23–47 years). All subjects were right-handed, and were free of other medical and psychiatric disorders that might affect brain function based on history and physical examination, laboratory evaluation, and MRI. None of the PWS were enrolled in speech therapy at the time of the scan. Their symptoms of stuttering ranged from mild to severe, as assessed from a recording of the speech during the scan when they were speaking spontaneously.

1.2. Speech tasks

A detailed discussion of the speech and language tasks is presented in Braun et al. (1997). Subjects were scanned during two fluency-evoking conditions: (1) while pacing their speech at approximately 92 beats per minute during generation of a narrative (subjects practiced with a metronome beating at this rate before the scan began, but it was turned off 30 s prior to scan onset); and (2) while singing a familiar song of their choice (e.g., a nursery rhyme). All subjects were fluent when speech was produced under these conditions. Subjects were also scanned during two dysfluency-evoking conditions: (3) while constructing sentences that included a verb assigned at the onset of scanning; and (4) while narrating an event or series of events, using normal speech rate, rhythm and intonation (CSP). Subjects were also scanned (5) at rest.

All tasks were presented in a counter-balanced order, with baseline scans occurring initially, and at the end of the study.

1.3. Speech recording, acoustic analysis, and derivation of weighted dysfluency scores

Subjects' speech output was recorded along with a computer generated signal, identifying the start of the H₂¹⁵O scan. The data were digitized with a sampling rate of 5000 Hz, using an anti-aliasing filter of 2000 Hz. Using MITSYN software, the leading edge of the computer generated signal was identified, and the digitized speech sample (from 20 s before to 40 s following the start of the scan) was played back and dysfluent symptoms were scored as present (+1) or absent (0), in 2-s epochs.

Phonation time was assessed using the Real Pitch module of the Kay Elemetrics CSL program uses an algorithm based on the number of zero crossings to measure percent voicing within a sample of speech. The 40 s of speech after the bolus was injected were analyzed using this program to determine percent voicing.

A complete description of how weighted dysfluency scores were derived is contained in Braun et al. (1997). These scores, which reflect the probable contribution of speech symptoms to the PET image, were derived by solving the Kety flow model for predicted tissue activity in the case of changing flow; calculating the sensitivity (derivative) of the predicted PET tissue activity to the flow at each second during the period sampled; and normalizing the resultant sensitivity curve by setting this to an integral of 1.0. The weighting function, was shifted -5 s from the start of scan to account for the approximate hemodynamic response time. Subjects' scores during each scan were determined by summing the sensitivity values [dysfluency scores (0 or 1) \times the associated weights at each point throughout the period during which speech was sampled and scored], such that maximal dysfluency (i.e., evident during each epoch of this period) would be associated with a maximum score of 1.0. These scores were used as confounding covariates in the SPM analyses described below.

1.4. Scanning methods

Details of the scanning methods are identical to those reported in Braun et al. (1997). The PET scans were performed on a Scanditronix PC2048-15B tomograph (Uppsala, Sweden) with an axial and in-plane resolution of 6.5 mm. Fifteen planes, offset by 6.5 mm (center to center) were acquired simultaneously. Subjects' eyes were patched, and head motion was restricted during the scans with a thermoplastic mask. Each scan followed intravenous bolus injection of 30 mCi of $H_2^{15}O$. Scans began automatically when the radioactive count rate reached a threshold value approximately 20 s after injection and continued for approximately 4 min. Speech tasks were initiated 30 s prior to injection of the radiotracer, and continued throughout the scan. Studies were separated by 10-min intervals. Emission data were corrected for attenuation by means of a transmission scan.

2. PET data analysis

PET scans were registered and stereotaxically normalized using Statistical Parametric Mapping software (Wellcome Department of Cognitive Neurology, London, UK). Images were smoothed with a Gaussian filter (15 mm \times 15 mm \times 9 mm in x , y , and z axes) to accommodate intersubject differences in anatomy, and spatially normalized to produce images in a common stereotaxic (Talairach) space. Differences in global activity were controlled for by proportional normalization.

Using SPM, we contrasted conditions using a *multiple subjects with conditions and covariates* design with dysfluency scores entered as a confounding covariate. We initially performed pairwise contrasts — each fluency-evoking condition was contrasted independently with rest; each dysfluency-evoking condition was similarly contrasted — in both PWS and controls. In order to identify the features shared by all conditions, a conjunction analysis was performed separately

for PWS and controls and the results were masked with the pairwise contrasts to insure that voxels identified in this fashion represented significant activations in all conditions. The conjunction maps were additionally masked with the contrasts outlined in the next paragraph in order to remove voxels in which there were any significant differences between fluency- and dysfluency-evoking conditions.

In order to determine which activations were greater under fluency-evoking than dysfluency-evoking conditions, four condition contrasts (both fluency- and both dysfluency-evoking conditions) were performed for PWS and controls. The results of these contrasts were then masked with the individual pairwise contrasts (paced speech minus rest AND singing minus rest) in order to assure that voxels identified as more active under fluency-evoking conditions were indeed activated when both fluency-evoking conditions were compared with rest.

Activations were then compared between groups in order to identify regions in which activity during fluency-evoking conditions in stuttering subjects significantly exceeded that observed under the same conditions in controls. The results of these contrasts — (fluency- and dysfluency-evoking conditions) in PWS minus (fluency- and dysfluency-evoking conditions) in controls — were masked with individual pair-wise contrasts (paced speech minus rest AND singing minus rest in PWS) in order to assure that voxels identified in this fashion were significantly activated when both fluency-evoking conditions were independently compared with rest in PWS.

3. Results

3.1. Acoustic analysis

Since one possible explanation for what is shared by these fluency-evoking conditions was increased phonation time or increased vowel duration, we determined whether these had been modified in the same way during both conditions. Direct comparison of vowel duration could only be achieved if the same words were spoken in both the narrative speech and paced sample, and if the rate of speech was the same between the two samples. Since this was not the case, increased phonation time was assessed.

To determine a representative percent voicing for speech, the mean percent voicing for the controls for the narrative speech sample was calculated. The mean and standard deviation of the percent voicing time was $29.8 \pm 9.0\%$. During paced speech, PWS were slightly greater than 1 standard deviation above the control group's percent voicing during narrative speech. Both groups increased percent voicing by greater than 1 standard deviation during singing. To demonstrate that this increase was due to singing and not the specific words used in the song, percent voicing was calculated when subjects spoke the words to the same song. Both groups were within 1 standard deviation of the control group's percent voicing for narrative speech.

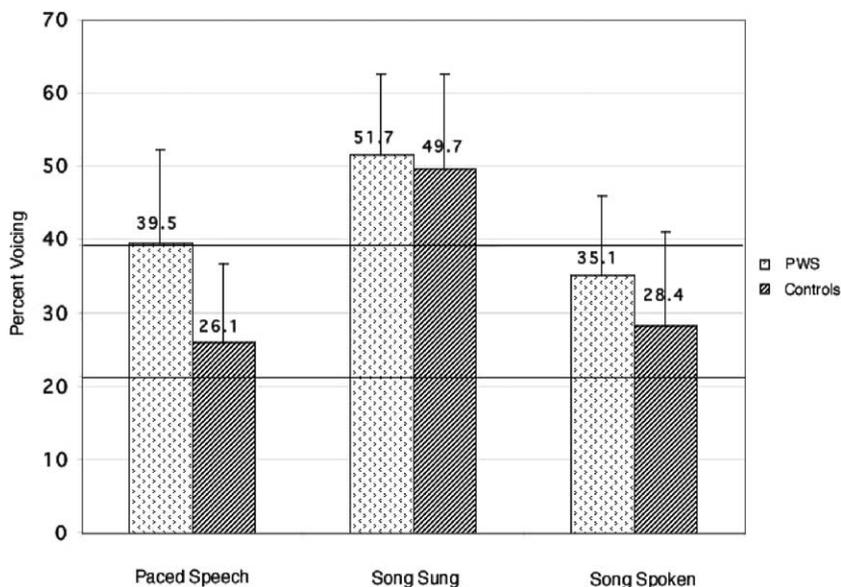


Fig. 1. Percent voicing for three speech tasks in both PWS and controls. Bars and error bars indicate means and standard deviations for this measure calculated during paced speech, singing the words to a familiar song, and speaking the words to the same song. Dark lines represent ± 1 standard deviation from the mean percent voicing measured in controls during narrative speech. Statistical comparisons are summarized in the [Section 3](#).

A *t*-test revealed significant differences between PWS and controls for the percent voicing during paced speech, but not during singing or speaking words to the same song. In other words, increased phonation time serves to evoke fluency during singing, but not during paced speech. Thus, this measure did not represent a common feature of both conditions. [Fig. 1](#) illustrates the percent voicing for the various tasks for both groups.

3.2. PET analysis

[Table 1](#) and [Fig. 2](#) illustrate regional activations that were equal in magnitude in fluency- and dysfluency-evoking conditions, compared to rest, in PWS and controls. These were typically bilateral and included regions that play a role in sensorimotor processing — precentral gyrus, cerebellum, insula and motor cingulate — and a restricted portion of the temporal gyrus — temporal pole and posterior STG and STS — in both hemispheres.

[Fig. 3](#) illustrates activations that were greater under fluency-evoking than dysfluency-evoking conditions in PWS and controls. Differences were most robust in the auditory cortices — including core and belt areas and extending into the anterior and posterior STG in both left and right hemispheres. Greater activation

Table 1

Regional activations that were equal in magnitude in fluency- and dysfluency-evoking conditions in stuttering subjects and controls

Region	Brod. no.	Control subjects								Stuttering subjects							
		Left hemisphere				Right hemisphere				Left hemisphere				Right hemisphere			
		Z-score	x	y	z	Z-score	x	y	z	Z-score	x	y	z	Z-score	x	y	z
Subcortical																	
Cerebellar vermis		5.10	-14	-64	-16	4.06	4	-72	-16	4.94	-2	-64	-20	4.99	2	-64	-20
Ventral thalamus		-	-	-	-	3.41	14	-8	8	-	-	-	-	4.05	14	-12	8
Temporal lobe																	
Temporal pole	38	4.11	-52	6	-8	3.88	48	6	-8	-	-	-	-	3.62	48	6	-8
Posterior STG and STS	22	5.23	-50	-26	4	6.35	54	-26	4	5.21	-52	-20	4	4.67	52	-26	4
Lateral premotor																	
Mid insula		3.64	-36	10	0	4.06	42	8	0	3.30	-42	6	0	3.11	32	12	4
Medial premotor																	
Anterior cingulate cortex	24, 32	3.93	-16	10	36	5.18	10	10	36	-	-	-	-	3.11	10	10	32
Primary motor																	
Dorsal precentral gyrus	4, 6	5.52	-46	-10	40	5.41	44	-14	40	5.26	-46	-16	40	4.32	52	-10	40

Significant conjunctions, masked as outlined in the Section 1 are tabulated along with Z-scores (representing local maxima) and associated Talairach coordinates.

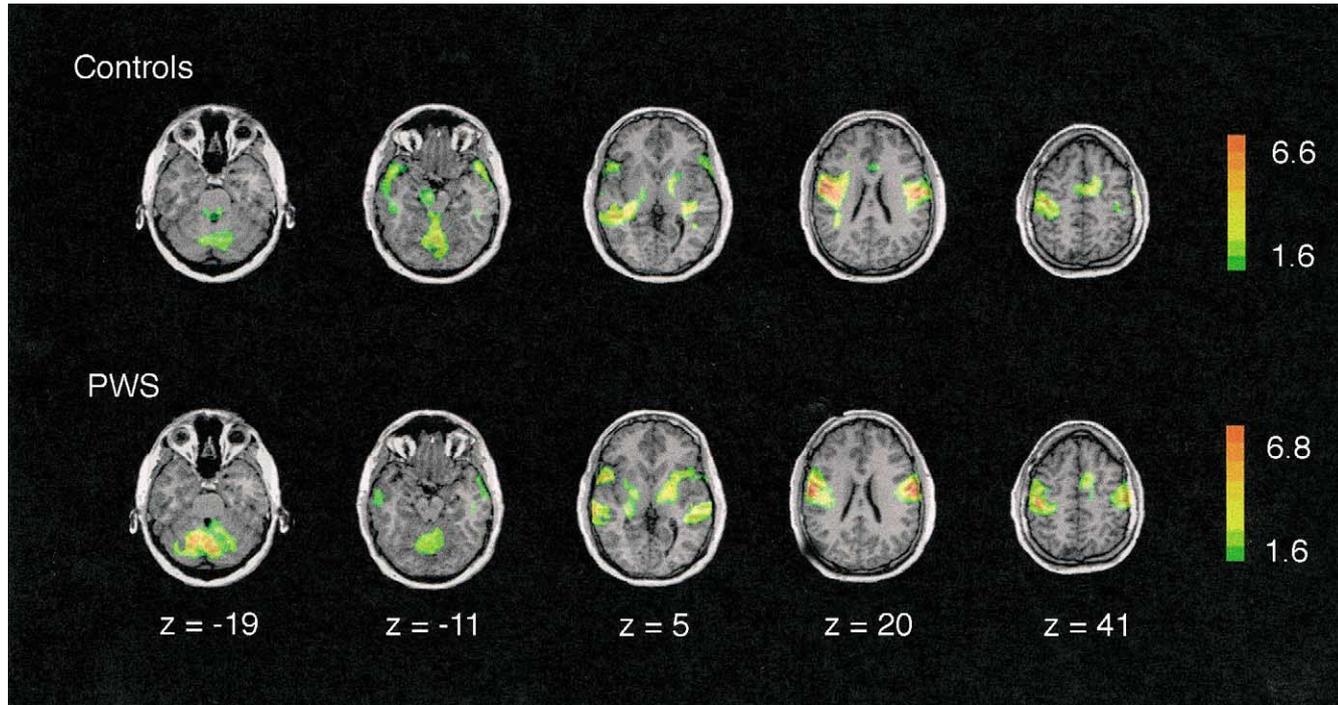


Fig. 2. Brain maps illustrating conjunctions between activations associated with the two fluency-evoking and two dysfluency-evoking tasks in controls (top row) and stuttering subjects (PWS, bottom row). Regions in which activations were equal in magnitude in all conditions are displayed on a standardized MRI scan, which was transformed linearly into stereotaxic (Talairach) space. Scans are displayed using neurological convention (left hemisphere is represented on the left). Planes of section relative to the bi-commissural line are indicated. Values are Z-scores representing the significance of voxel-wise increases in normalized rCBF. The range of scores is coded in the accompanying color table. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

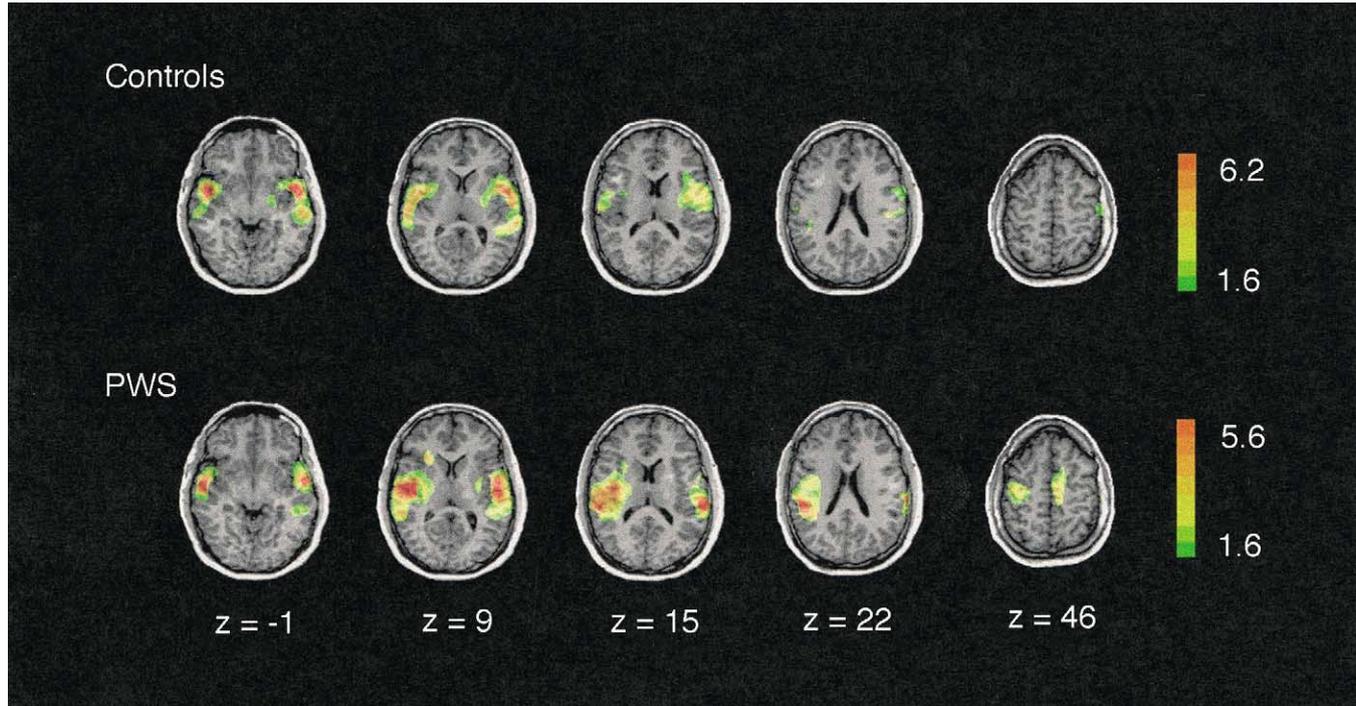


Fig. 3. Brain maps illustrating activations that were greater during fluency-evoking than dysfluency-evoking conditions in controls (top row) and stuttering subjects (PWS, bottom row). Statistical parametric maps are displayed on a standardized MRI scan as outlined in the legend to Fig. 2. Planes of section relative to the bi-commissural line are indicated. Values are Z-scores representing the significance of voxel-wise increases in normalized rCBF. The range of scores is coded in the accompanying color table. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Regions in which rCBF responses during fluency-evoking conditions were greater in both stuttering subjects and controls

Region	Brod. no.	Control subjects								Stuttering subjects							
		Left hemisphere				Right hemisphere				Left hemisphere				Right hemisphere			
		Z-score	x	y	z	Z-score	x	y	z	Z-score	x	y	z	Z-score	x	y	z
Subcortical																	
Posterior putamen		3.04	−30	4	4	3.00	30	−2	8	3.12	−30	−12	12	2.91	28	−8	8
Temporal lobe																	
Anterior STG	22	6.12	−48	0	4	5.82	46	−2	0	3.54	−52	−4	0	4.08	50	−6	4
Auditory core and belt	41/42	4.26	−60	−18	12	4.39	48	−16	12	3.98	−46	−14	8	3.44	48	−20	12
Posterior STG	22	4.05	−58	−26	12	4.30	52	−26	8	4.05	−54	−32	16	4.01	56	−28	16
Primary motor																	
Ventral precentral gyrus	4/6	4.77	−46	2	8	4.77	44	2	8	3.02	−44	−8	12	3.10	46	2	8

Regions in which differences between fluency- and dysfluency-evoking conditions were significant are tabulated along with Z-scores (representing local maxima) and associated Talairach coordinates.

Table 3
Regions in which rCBF responses during fluency-evoking conditions were greater in stuttering subjects than controls

Region	Brod. no.	Stuttering subjects							
		Left hemisphere				Right hemisphere			
		Z-score	x	y	z	Z-score	x	y	z
Temporal lobe									
Posterior STG and IPL	22/40	3.11	−40	−44	22	–	–	–	–
Anterior MTG and STS		2.61	−58	−10	−4	–	–	–	–
Parietal lobe									
SII and posterior insula	43	2.19	−44	−10	20	–	–	–	–
Lateral premotor									
Anterior insula		3.33	−24	20	8	–	–	–	–
Dorsal precentral gyrus	4/6	3.53	−32	−4	36	2.36	50	2	32
Medial premotor									
SMA	6	–	–	–	–	2.15	8	6	44
Anterior cingulate cortex	32	–	–	–	–	3.03	8	20	32

Regions in which differences between fluency and dysfluency are significantly larger in stuttering subjects are tabulated along with Z-scores (representing local maxima) and associated Talairach coordinates.

under fluency-evoking conditions was also found in the ventral precentral gyrus and posterior putamen in both groups in both left and right hemispheres.

Activation patterns were not identical, however, and the differences are summarized in *Tables 2 and 3*. Features that were common to both PWS and controls are included in *Table 2*.

Table 3 summarizes responses that were greater in PWS than controls. Stuttering subjects showed greater activation during fluency-evoking conditions in auditory cortices, somatosensory cortices, and insula within the left hemisphere. Responses were also greater in PWS in the dorsal portion of the precentral gyrus and midline cortices including the SMA and anterior cingulate.

4. Discussion

The purpose of this study was to determine what is shared by two effective but markedly different maneuvers — singing and pacing speech with a metronome — that might account for their common fluency-evoking effects in stuttering subjects. These tasks were selected because they are among the most successful at reducing dysfluency in a majority of PWS (*Andrews et al., 1982*).

Effects that are shared by these tasks might occur at the periphery, as well as centrally. Experimental research has demonstrated that a single mechanism, increased phonation time, as evidenced also by increased vowel durations, might explain improved fluency for both conditions. This is supported by the therapeutic literature, because increasing phonation time has also been shown to be an effective treatment (*Ingham et al., 1983*). As a measure of phonation time, we examined percent voicing during the two fluency-evoking tasks in PWS and controls and compared this with percent voicing measured during a narrative speech task in controls. If increases in this measure represented the mechanism by which these tasks produce their effects, we would have expected to see an increase during both. Since this was not found, it is unlikely that this peripheral mechanism accounts for the fluency-evoking effects of both paced speech and singing.

We, therefore, used PET to characterize changes in brain activity elicited by these tasks, comparing them with resting scans and contrasting responses with those elicited by tasks that typically elicit dysfluent speech in PWS. We paid particular attention to changes that might support a common mechanism, specifically the interrelationships between motor activity and auditory feedback.

We first characterized conjunctions — areas that were equally active, vs. rest, in both fluency and dysfluency conditions — in PWS as well as controls. We expected that these regions would include sensorimotor areas related to speech motor control and auditory areas that process speech and voice. However, because responses do not differ between conditions, they would not be expected to play a significant role in the fluency-evoking mechanisms associated with singing or paced speech.

We next identified areas that were either uniquely activated during fluency-evoking conditions, or in which the magnitude of activation was significantly greater during fluency-evoking than dysfluency-evoking tasks. Activity in these regions should more likely be directly related to the fluency-evoking mechanisms in question.

Since they were characterized in both stuttering subjects and controls, the findings can be interpreted in distinct ways. Regional activations might be due to the sensorimotor or cognitive demands of the fluency-evoking tasks themselves. In this case, the same responses should be detected in PWS as well as controls. On the other hand, responses might represent idiosyncratic CNS responses in stuttering subjects to the constraints of the fluency-evoking tasks. In this case, responses would be detected in PWS but not controls.

Many of the areas that were detected in the conjunction analysis — that is, activated during both fluency-evoking and dysfluency-evoking conditions — have been shown to play a role in speech motor control. These activations, typically bilateral, included the cerebellar vermis, which is involved in timing and sequencing of motor behaviors; the mid portion of the insula, which functions as part of the lateral premotor system; the cingulate motor area and the dorsal portion of the primary motor cortex. Many of these regions have been shown to be activated during speech articulation in control subjects (DeNil, Kroll, & Houle, 2001; Fox et al., 2000; Murphy et al., 1997).

Auditory areas that were active during both fluency- and dysfluency-evoking conditions included the posterior portion of the STG extending into the superior temporal sulcus, and the temporal pole, and are likely activated by the subjects' own speech and voice produced during all of these tasks. Nevertheless, they represent only a restricted portion of the auditory system.

Indeed, a much wider array of areas that appear to participate in self-monitoring of speech and voice were more active during fluency-evoking than during dysfluency-evoking conditions, in both PWS and control subjects. These regions include, in right and left hemispheres, both anterior and posterior auditory association areas as well as core and belt areas surrounding the primary auditory cortex. These regions encompass those that are activated by voice (Belin, Zatorre, Lafaille, Ahad, & Pike, 2000) and intelligible speech (Scott, Blank, Rosen, & Wise, 2000), and those that are activated when subjects monitor their speech output under conditions in which auditory verbal feedback is altered (McGuire, Silbersweig, & Frith, 1996). In our study, given that the task was to maintain a speech rate in the absence of an external stimulus, it is not surprising that areas involved in self-monitoring were activated.

Similar areas of activation were found in previous neuroimaging studies of singing (Jeffries, Fritz, & Braun, 2003; Perry et al., 1999), and activation of auditory association areas during fluent speech production in PWS is supported by previous literature (Braun et al., 1997; Fox et al., 1996, 2000).

In the present study, increased activation of the auditory regions during both fluency-evoking conditions suggests that the hypothesis that these maneuvers result

in decreased attention to vocal output (inducing fluency in this fashion) is likely to be wrong. Our findings suggest an alternative explanation — that these tasks may work by enabling more efficient use of auditory information in order to monitor and correct speech. This possibility is supported by the fact that activation of speech-related motor regions is also significantly greater during both fluency-evoking conditions. These include the ventral precentral gyri (which regulate movements of the lips, tongue, jaw, and larynx), and the putamen (central constituent of a circuit connecting basal ganglia, thalamus, and cortex which organizes complex sequences of movements). Co-activation of regions involved in speech production as well as auditory feedback might reflect more effective coupling of auditory and motor systems under fluency-evoking conditions. Since this pattern was seen in both PWS and controls, such an effect may represent a feature of the fluency-evoking tasks themselves.

On the other hand, the direct comparison of responses in PWS and controls pinpointed a number of regions in which fluency-evoking conditions evoked a more robust response in stuttering subjects. These included the anterior MTG and anterior STS — regions that appear to be selectively activated by voice (Belin et al., 2000) and intelligible speech (McGuire et al., 1996; Scott et al., 2000) — suggesting that the fluency-evoking conditions may enhance self-monitoring to a greater degree in PWS than in controls. These tasks also elicited a greater response in PWS in other auditory association areas including the posterior STG, extending in this case into the supramarginal gyrus. The SMG is thought to function, in part, as an auditory-motor interface (Hickok, 2001) supporting the idea that these maneuvers may facilitate more effective coupling of auditory and motor systems in PWS.

Activity in other sensorimotor areas was selectively enhanced in stuttering subjects as well. These included the anterior insula, which appears to play a role in articulatory planning (Dronkers, 1996) and in the second somatosensory area (SII) which may process feedback from the larynx and oral articulators. PWS also showed more robust responses in the precentral gyri bilaterally and in midline premotor areas including the SMA and anterior cingulate cortex.

It is interesting that most of these responses are strongly lateralized to the left hemisphere. The role played by left and right hemispheres in the pathophysiology of stuttering remains controversial, with various models implicating either hemisphere in both the generation of stuttering symptoms and the induction of fluency. The present results indicate that while fluency-evoking tasks may facilitate auditory-motor integration by producing bilateral cortical responses in both PWS and controls, these tasks selectively elicit greater responses in auditory and motor cortices in the left hemisphere of stuttering subjects. This suggests a role for the left hemisphere in compensatory processes that enable fluency.

In summary, the goal of this study was to characterize the common features of two successful but markedly different fluency-evoking conditions — paced speech and singing. To address this issue, we considered both peripheral and

central effects of these maneuvers, and compared these responses in stuttering subjects and controls. Using the degree of stuttering measured during image acquisition as a covariate in our analyses reduced the impact of stuttered speech on the PET signal and highlighted patterns of CNS activity related to the tasks themselves. We must acknowledge that because only two fluency-evoking conditions were compared, other conditions need to be assessed in the future in order to be able to generalize about brain regions that may be selectively activated by these procedures. Furthermore, future studies would be strengthened by including additional measures of peripheral speech production and auditory function, so that performance can be more directly correlated with brain imaging data. Nevertheless, our results do suggest that a common mechanism for eliciting fluency may relate to more efficient coupling of auditory and motor systems — that is, more effective self-monitoring (which may be reflected in increased activity in auditory association areas), may allow motor areas controlling the larynx and the oral articulators (also activated by both fluency-evoking conditions) to more effectively modify speech. While bilateral responses were seen in both PWS and controls, the fluency-evoking tasks elicited more robust activation of auditory and motor regions within the left hemisphere of stuttering subjects.

References

- Adams, M., Runyan, C., & Mallard, A. R. (1975). Air flow characteristics of the speech of stutterers and nonstutterers. *Journal of Fluency Disorders*, 1, 3–12.
- Andrews, G., Howie, P., Dozsa, M., & Guitar, B. (1982). Stuttering: Speech pattern characteristics under fluency-inducing conditions. *Journal of Speech and Hearing Research*, 25, 208–216.
- Belin, P., Zatorre, R. J., Lafaille, P., Ahad, P., & Pike, B. (2000). Voice-selective areas in human auditory cortex. *Nature*, 403, 309–312.
- Blood, G. W. (1985). Laterality differences in child stutterers: Heterogeneity, severity levels, and statistical treatments. *Journal of Speech & Hearing Disorders*, 50(1), 66–72.
- Blood, I. M., & Blood, G. W. (1986). Relationship between specific disfluency variables and dichotic listening in stutterers. *Perceptual & Motor Skills*, 62(1), 337–338.
- Boutsen, F. R., Brutton, G. J., & Watts, C. R. (2000). Timing and intensity variability in the metronomic speech of stuttering and nonstuttering speakers. *Journal of Speech, Language and Hearing Research*, 43, 513–520.
- Braun, A. R., Varga, M., Stager, S., Schulz, G., Selbie, S., Maisog, J. M., Carson, R. E., & Ludlow, C. L. (1997). Altered patterns of cerebral activity during speech and language production in developmental stuttering. *Brain*, 120(5), 761–784.
- Brayton, E., & Conture, E. (1978). Effects of noise and rhythmic stimulation on the speech of stutterers. *Journal of Speech and Hearing Research*, 21, 285–294.
- Colcord, R. D., & Adams, M. R. (1979). Voicing duration and vocal SPL changes associated with stuttering reduction during singing. *Journal of Speech & Hearing Research*, 22(3), 468–479.
- DeNil, L. F., Kroll, R. M., & Houle, S. (2001). Functional neuroimaging of cerebellar activation during single word reading and verb generation in stuttering and nonstuttering adults. *Neuroscience Letters*, 302, 77–80.

- Dronkers, N. F. (1996). A new brain region for coordinating speech articulation. *Nature*, *384*, 159–161.
- Fox, P. T., Ingham, R. J., Ingham, J. C., Hirsch, T. B., Downs, J. H., Martin, C., Jerabek, P., Glass, T., & Lancaster, J. L. (1996). A PET study of the neural systems of stuttering. *Nature*, *382*, 158–162.
- Fox, P. T., Ingham, R. J., Ingham, J. C., Zamarripa, F., Xiong, J.-H., & Lancaster, J. L. (2000). Brain correlates of stuttering and syllable production: A PET performance-correlation analysis. *Brain*, *123*, 1985–2004.
- Hall, J., & Jerger, J. (1978). Central auditory function in stutterers. *Journal of Speech and Hearing Research*, *21*, 324–337.
- Hanna, R., & Morris, S. (1977). Stuttering, speech rate, and the metronome effect. *Perceptual & Motor Skills*, *44*(2), 452–454.
- Hannley, M., & Dorman, M. (1982). Some observations on auditory function and stuttering. *Journal of Fluency Disorders*, *7*, 93–108.
- Hickok, G. (2001). Functional anatomy of speech perception and speech production: Psycholinguistic implications. *Journal of Psycholinguistic Research*, *30*, 225–235.
- Hutchinson, J., & Navarre, B. (1977). The effect of metronome-pacing on selected aerodynamic patterns of stuttered speech: Some preliminary observations and interpretations. *Journal of Fluency Disorders*, *2*, 189–204.
- Ingham, R. J., & Andrews, G. (1973). Behavior therapy and stuttering: A review. *Journal of Speech & Hearing Disorders*, *38*(4), 405–441.
- Ingham, R. J., Montgomery, J., & Ulliana, L. (1983). The effect of manipulating phonation duration on stuttering. *Journal of Speech & Hearing Research*, *26*(4), 579–587.
- Janssen, P., & Wieneke, G. (1987). The effects of fluency inducing conditions on the variability in the duration of laryngeal movements during stutterers' fluency speech. In H. F. M. Peters & W. Hulstijn (Eds.), *Speech motor dynamics in stuttering* (pp. 337–344). New York: Springer-Verlag.
- Jeffries, K. J., Fritz, J. B., & Braun, A. R. (2003). Words in melody: An H(2)150 PET study of brain activation during singing and speaking. *Neuroreport*, *14*(5), 749–754.
- McGuire, P. K., Silbersweig, D. A., & Frith, C. D. (1996). Functional neuroanatomy of verbal self-monitoring. *Brain*, *119*, 907–917.
- Murphy, K., Corfield, D. R., Guz, A., Fink, G. R., Wise, R. J. S., Harrison, J., & Adams, L. (1997). Cerebral areas associated with motor control of speech in humans. *Journal of Applied Physiology*, *83*(5), 1438–1447.
- Perry, D. W., Zatorre, R. J., Petrides, M., Alivisatos, B., Meyer, E., & Evans, A. C. (1999). Localization of cerebral activity during simple singing. *Neuroreport*, *10*, 3453–3458.
- Samelin, R., Schnitzler, A., Schmitz, F., Jancke, L., Witte, O. W., & Freund, H.-J. (1998). Functional organization of the auditory cortex is different in stutterers and fluent speakers. *Neuroreport*, *9*, 2225–2229.
- Scott, S. K., Blank, C. C., Rosen, S., & Wise, R. J. S. (2000). Identification of a pathway for intelligible speech in the left temporal lobe. *Brain*, *123*, 2400–2406.
- Stager, S. V. (1990). Heterogeneity in stuttering: Results from auditory brainstem response testing. *Journal of Fluency Disorders*, *15*, 9–19.
- Stager, S. V., Denman, C., & Ludlow, C. L. (1997). Modifications in aerodynamic variables by persons who stutter under fluency-evoking conditions. *Journal of Speech, Language and Hearing Research*, *40*, 832–847.
- Toscher, M., & Rupp, R. (1978). A study of the central auditory processes in stutterers using the Synthetic Sentence Identification (SSI) test battery. *Journal of Speech and Hearing Research*, *21*, 779–792.
- Webster, R. L., & Lubker, B. B. (1968). Interrelationships among fluency producing variables in stuttered speech. *Journal of Speech and Hearing Research*, *11*, 754–766.
- Wu, F. C., Maguire, G., Riley, G., Fallon, J., LaCasse, L., Chin, S., Klein, E., Tang, C., Cadwell, S., & Lottenberg, S. (1995). A positron emission tomography [¹⁸F]deoxyglucose study of developmental stuttering. *Neuroreport*, *6*, 501–505.

CONTINUING EDUCATION

Common features of fluency-evoking conditions studied in stuttering subjects and controls: an H₂¹⁵O PET study

QUESTIONS

1. The most robust effect of fluency-evoking conditions in both stuttering subjects and controls is found in the:
 - a. somatosensory cortex
 - b. auditory cortex
 - c. subcortical structures
 - d. motor cortex
2. Fluency-evoking conditions have a stronger effect in stuttering subjects than control in the:
 - a. right hemisphere
 - b. left hemisphere
 - c. bilaterally
 - d. subcortically
3. The strongest evidence from this study is that the common features of the fluency-evoking conditions that were investigated relate to:
 - a. central mechanisms
 - b. peripheral mechanisms
 - c. both
 - d. neither
4. A plausible model based on the results of this study is that fluency-evoking tasks may work by facilitating:
 - a. the effects of auditory feedback on the motor system
 - b. the impact of auditory self-monitoring on the cerebellum
 - c. the use of proprioceptive information from the oral articulators by the motor system
 - d. coupling of the somatosensory and motor systems
5. Both fluency- and dysfluency-evoking tasks are associated with activation of the:
 - a. cerebellum
 - b. caudate nucleus
 - c. angular gyrus
 - d. hippocampus