Analysis of High-Frequency Electroencephalographic-Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson’s Disease

**Purpose:** Corticomuscular electroencephalographic-electromyographic (EEG-EMG) coherence elicited by speech and nonspeech oromotor tasks in healthy participants and those with Parkinson’s disease (PD) was examined. Hypotheses were the following: (a) corticomuscular coherence is demonstrable between orbicularis oris (OO) muscles’ EMG and scalp EEG recording; (b) the presence, location, and magnitude of coherence is task specific; (c) differences in corticomuscular coherence patterns exist between healthy and PD participants; and (d) differences will manifest as either increased or decreased coherence values in certain frequency bands, with EEG localization at primary sensorimotor cortex and/or supplementary motor area (SMA).

**Method:** Simultaneous EEG, EMG (OO), and speech samples were recorded on 20 healthy and 20 PD participants during speech and nonspeech tasks. Fast Fourier transform and coherence analysis was performed with Neuroscan software on 1,000 randomly generated epochs per task per group. Corticomuscular coherence was analyzed between each EEG electrode and right and left superior and inferior OO muscles up to 200 Hz. Significant coherence peaks exceeded 95% confidence limits (.003).

**Results:** Corticomuscular coherence existed for both groups and for all tasks, but to varying degrees in primary sensorimotor cortex and SMA.

**Conclusions:** Results support task specificity for both groups and, in PD, a diminished modulation flexibility linked to the sensorimotor area and reduced corticomuscular coherence at the SMA.

**KEY WORDS:** corticomuscular coherence, Parkinson’s disease, speech, nonspeech

The cortical mechanisms that govern motor aspects of speech production have not been precisely defined. Classic studies by Jasper (1958) and Penfield and Roberts (1959) showed that mouth movements and vocalizations could be elicited by stimulation over both lateral sensorimotor cortices and the supplementary motor area (SMA). Functional imaging studies have confirmed the involvement of the bilateral sensorimotor cortex, SMA, and the insula in speech production (Ackermann & Riecker, 2004; Lotze, Seggewies, Erb, Grodd, & Birbaumer, 2000). Electroencephalographic (EEG) examinations of the Bereitschaftspotential, a cortical “readiness” potential that precedes voluntary movement, have provided another source of evidence for the cortical contributions to speech motor control and how this control may differ from nonspeech
oral movements (Deecke, Engel, Lang, & Kornhuber, 1986; Tarkka, 2001; Wohlert, 1993).

Complementing the studies that have focused on time domain analysis, frequency domain studies of corticomuscular coherence have offered insight to the cortical control of movement, particularly with regard to limbs (e.g., Conway et al., 1995; Halliday, Conway, Farmer, & Rosenberg, 1998; Marsden et al., 2000; Mima & Hallett, 1999). Coherence is a correlation measure of linear relatedness between two waveforms as a function of frequency, and coherence values range from 0 to 1 (Halliday et al., 1996). Studies using this analysis technique have shown that the sensorimotor cortex manifests particular frequency bands in various combinations to produce the appropriate muscle activation. These studies have variably used magnetoencephalography, implanted electrodes, epicortical contacts, and scalp EEG recording (Conway et al., 1995; Halliday et al., 1996, 1998; Marsden et al., 2000; Mima & Hallett, 1999). By examining multiple sites across the cortex with EEG recording, it is possible to obtain the following pieces of information: (a) the frequency bands at which corticomuscular coherence is present, (b) the cortical locations at which the coherence is present, and (c) the magnitude of the coherence peaks in relative terms. A coherence value of 1 indicates perfect correlation between the two waveforms, whereas a coherence value of 0 indicates no waveform correlation. Coherence is independent of the amplitude of the two waveforms. Thus, this measure can be thought to reflect coupling between electrophysiology mechanisms in the control of movement production.

Corticomuscular coherence studies of normal movement control have demonstrated oscillations coherent between the contralateral sensorimotor cortex (EEG) and muscle (electromyographic [EMG]) during voluntary muscle contractions (Conway et al., 1995; Salenius, Portin, Kajola, Salmelin, & Hari, 1997). These studies have found that the 15–30-Hz band is activated during weak and moderate tonic contractions, whereas the 30–50-Hz band may be important for strong contractions and phasic movements (Halliday et al., 1998; Salenius et al., 1997). For phasic movements, investigators have identified frequency changes that are known as event-related coherence and event-related desynchronization/synchronization (Leocani, Toro, Manganotti, Zhuang, & Hallett, 1997). These observations have been used to hypothesize that synchronization at specific frequencies in both the spatial and time domain are combined to produce coordinated voluntary movement (Marsden et al., 2000).

The analysis of coherence patterns and power spectrum changes during muscle contraction in disease states offers a window to the abnormal corticomuscular relations underlying movement disorders. A number of findings have been reported for Parkinson’s disease (PD). Brown and colleagues demonstrated the marked reduction of the “Piper rhythm” in patients with PD (Brown, Salenius, Rothwell, & Hari, 1998). The Piper rhythm is the rhythmic 40-Hz EMG oscillation present during strong voluntary contraction in healthy humans. It was hypothesized that the inability to produce this high-frequency EMG discharge might relate to decreased initiation speed in PD. These authors further demonstrated that power spectrum and corticomuscular coherence in the 10-Hz region were abnormally increased in the patients with PD while they were in the nonmedicated “off” condition, but this activity partially normalized when levodopa was administered. Thus, coherence measures seem to capture some meaningful aspect of the underlying pathophysiology of this movement disorder through the dopaminergic basal ganglia-cortical circuitry (Salenius, Avikainen, Kaakkola, Hari, & Brown, 2002).

Coherence analysis to examine corticomuscular activation relations in the context of speech production has not been previously explored. Indeed, most of the coherence studies of motor control have examined relatively simple movements of the fingers and limbs. The paradigm of coherence analysis does not itself prohibit the examination of more complex movements, and it should theoretically have the potential to reveal important information about normal and abnormal speech motor control. Because articulatory and phonatory deficits are present in a majority of patients with PD, and because corticomuscular coherence pattern abnormalities have been documented in limb movement for this population, this was thought to be a fruitful test case for coherence analysis in speech production. Further, by examining EMG data elicited by a sampling of oral motor activities, ranging from sustained orolabial nonspeech movement at one end to connected speech on the other, task-specific differences in corticomuscular coherence may be revealed. Such information may inform the ongoing debate concerning the relation between the neural control of speech and nonspeech movements, as well as uncover task-specific abnormalities in PD (e.g., Ballard, Robin, & Folkins, 2003; Weismer, in press; Ziegler, 2003).

The purpose of this investigation was to determine whether coherence analysis could reveal frequency domain differences between cortical control of EMG data elicited by speech and nonspeech oromotor tasks in participants with PD and healthy control speakers. Based on previous reports of normal and abnormal corticomuscular coherence in limb control, it was hypothesized that (a) corticomuscular coherence is demonstrable between the orbicularis oris (OO) muscles’ EMG and scalp EEG data; (b) the presence, location, and magnitude of this coherence will vary with task; (c) abnormalities in corticomuscular coherence patterns will emerge for participants with PD as compared with healthy control speakers; and (d) these abnormalities will manifest as either increased or decreased coherence values with peak
spectral values within certain frequency bands, with EEG localization consistent with primary sensorimotor cortex (lateral central area) and/or SMA (midline frontal).

**Method**

**Participants**

Twenty persons with PD without postural tremor or myoclonus (PD group) and 20 sex- and age-matched (±2 years) controls (control group) participated in this study (see Table 1). Each group had 16 men and 4 women. The average age was 71.8 years (range = 56–84, SD = 7.6) for the PD group and 72.5 years (range = 56–87, SD = 7.05) for the control group. This age difference was not significant (p = .78). All participants were right-handed.

PD was diagnosed as a chronic progressive syndrome with two of three cardinal features of rest tremor, bradykinesia, and rigidity, without evidence of a secondary cause or atypical features (Hughes, Ben-Shlomo, Daniel, & Lees, 1992; Hughes, Daniel, Blankson, & Lees, 1993). The Unified Parkinson’s Disease Rating Scale (UPDRS) motor subsection scores (Fahn, Elton, & Members of the UPDRS Development Committee, 1987), and Hoehn and Yahr staging (Hoehn & Yahr, 1967) were recorded for each participant with PD (see Table 1). The average “on” UPDRS score at testing was 22.3, the average Hoehn and Yahr stage was 2.1, and the average speech UPDRS subscale rating was 1.45 (range = 1–2, SD = 0.51). Exclusion criteria included the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2000) criteria for dementia or a Mini-Mental State Examination score of <27 (Folstein, Folstein, & McHugh, 1975). Control participants were phone screened for a history of neurological problems and then examined on the day of testing for the presence of tremor, rigidity, bradykinesia, spasticity, or gait or balance abnormality. No participants were excluded on the basis of these criteria.

All participants in the PD group were responsive to dopamine replacement therapy per medical records, and data were collected in a self-reported “on” state, 1 to 3 hr after taking medications. UPDRS scores collected immediately before data collection are presented in Table 1. In addition, the speech abnormalities exhibited by these patients during data collection were regarded as mild and did not interfere with intelligibility in conversational speech or in the speech tasks, as determined by the examiners. When present, the dysarthric features consisted of mild hypophonia, mild monotonicity, and/or mild articulatory imprecision with reduced articulatory excursions. No other perceptual features were noted, and no features associated with a diagnosis other than mild hypokinetic dysarthria were exhibited by any of the participants. Prominent speech characteristics identified by the investigators collecting the speech samples and by two independent judges not associated with this study are summarized in Table 1.

Both the mild dysarthria presentation and the collection of data during the medicated “on” state were critical to the interpretability of the corticomuscular coherence pattern data in this first examination of speech. It was essential that the participants could perform the speech and nonspeech tasks as instructed to obtain comparable data sets between the normal and disordered groups. This provided for a stringent test case for the coherence hypotheses, particularly given that other investigations have shown a tendency for dopamine therapy to partially normalize some coherence parameters (Salenius et al., 2002). In other words, if coherence pattern differences were found in this investigation, they could be more confidently attributed to underlying pathology in the PD group than to inherent task performance differences between the two groups.

The Mayo Clinic and Arizona State University institutional review boards approved all procedures, and informed consent was obtained for all participants.

**Study Design and Determination of Subject Size**

The confidence limit value for coherence, above which coherence values are considered to be significant, decreases as the number of analyzed epochs increases (Halliday et al., 1996). The mathematical consequence of increasing epochs in the calculation of coherence is the reduction of spurious peaks and the fortification of robust peaks, and Mima and Hallett (1999) found that 100–300 epochs were sufficient for evaluating corticomuscular coherence peaks in limb movements. Our pilot work revealed the presence of coherence peaks in certain tasks with approximately 60–80 artifact-free epochs per subject; however, spurious peaks were common. Given that six tasks were sampled for each participant in this study, it would have been logistically difficult to collect the requisite number of epochs to conduct primary inrasubject analyses. Therefore, we adopted a group design, whereby artifact-free epochs were pooled within task and group, which provided for a robust coherence analysis.1

1Although this method of pooling epochs across participants has not been reported previously, there is no obvious contraindication, as each epoch is essentially an independent normalized entity. This method allowed us to increase the likelihood of robust, and presumably meaningful, coherence peaks while reducing the occurrence of spurious coherence spectra. To assess the validity of this novel procedure, all corticomuscular coherence data calculated for individual participants were examined post hoc to determine the extent to which their patterns mirrored those of the pooled epoch data. As reported herein, all significant findings of the pooled epoch data were apparent in the individual coherence data. This procedure allowed us to retain our discriminative task set without overtaxing our participants.
Selected intrasubject analyses were then conducted post hoc to verify the pooled epoch findings.

Through a priori calculations, it was determined that 1,000 epochs per task would permit us to detect small peak levels of coherence with a 95% confidence limit value of .003 (Halliday et al., 1996). This goal was attainable by analyzing 50 artifact-free epochs per each of the 20 participants for each task, for 1,000 total pooled epochs per task per group. Therefore, 20 participants per group were recruited.

Table 1. Descriptive data for all control (C) and Parkinson’s disease (P) participants including Hoehn and Yahr staging (0–5), Unified Parkinson’s Disease Rating Scale (UPDRS) motor section (0–108), and speech section (0–4).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Hoehn and Yahr</th>
<th>Motor UPDRS</th>
<th>Speech UPDRS</th>
<th>Age</th>
<th>Sex</th>
<th>Speech characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>70</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>72</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>66</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>87</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>73</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>74</td>
<td>M</td>
<td>—</td>
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<tr>
<td>C7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>74</td>
<td>M</td>
<td>—</td>
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<td>C8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>81</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C9</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>56</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>C10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>82</td>
<td>M</td>
<td>—</td>
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<tr>
<td>C11</td>
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<td>—</td>
<td>—</td>
<td>63</td>
<td>F</td>
<td>—</td>
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<td>C12</td>
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<td>—</td>
<td>72</td>
<td>F</td>
<td>—</td>
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<td>C13</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>71</td>
<td>M</td>
<td>—</td>
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<tr>
<td>C14</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>75</td>
<td>M</td>
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<tr>
<td>C15</td>
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<td>—</td>
<td>—</td>
<td>72</td>
<td>F</td>
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<tr>
<td>C16</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>72</td>
<td>M</td>
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<tr>
<td>C17</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>78</td>
<td>M</td>
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</tr>
<tr>
<td>C18</td>
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<td>—</td>
<td>—</td>
<td>70</td>
<td>F</td>
<td>—</td>
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<td>C19</td>
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<td>69</td>
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<tr>
<td>C20</td>
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<td>—</td>
<td>—</td>
<td>73</td>
<td>M</td>
<td>—</td>
</tr>
<tr>
<td>P21</td>
<td>2</td>
<td>17</td>
<td>1</td>
<td>77</td>
<td>M</td>
<td>No significant dysarthria noted</td>
</tr>
<tr>
<td>P22</td>
<td>2</td>
<td>33</td>
<td>2</td>
<td>76</td>
<td>M</td>
<td>Moderate hypophonia; mild articulatory imprecision</td>
</tr>
<tr>
<td>P23</td>
<td>2</td>
<td>25</td>
<td>2</td>
<td>77</td>
<td>M</td>
<td>Slightly reduced loudness</td>
</tr>
<tr>
<td>P24</td>
<td>2.5</td>
<td>31</td>
<td>2</td>
<td>67</td>
<td>M</td>
<td>No significant dysarthria noted</td>
</tr>
<tr>
<td>P25</td>
<td>2.5</td>
<td>25</td>
<td>2</td>
<td>71</td>
<td>M</td>
<td>Moderate hypophonia; mild articulatory imprecision</td>
</tr>
<tr>
<td>P26</td>
<td>2</td>
<td>9.5</td>
<td>1</td>
<td>62</td>
<td>F</td>
<td>Mild hypernasality</td>
</tr>
<tr>
<td>P27</td>
<td>2</td>
<td>27</td>
<td>2</td>
<td>82</td>
<td>M</td>
<td>Moderate hypophonia; tendency toward rapid rate</td>
</tr>
<tr>
<td>P28</td>
<td>2</td>
<td>23</td>
<td>1</td>
<td>68</td>
<td>M</td>
<td>Mild hypophonia</td>
</tr>
<tr>
<td>P29</td>
<td>2</td>
<td>18</td>
<td>2</td>
<td>77</td>
<td>M</td>
<td>Mild monotone</td>
</tr>
<tr>
<td>P30</td>
<td>2</td>
<td>31</td>
<td>2</td>
<td>74</td>
<td>M</td>
<td>Moderate hypophonia</td>
</tr>
<tr>
<td>P31</td>
<td>2</td>
<td>22</td>
<td>1</td>
<td>74</td>
<td>F</td>
<td>Mild hypophonia</td>
</tr>
<tr>
<td>P32</td>
<td>3</td>
<td>27</td>
<td>1</td>
<td>78</td>
<td>M</td>
<td>Mild consonant imprecision</td>
</tr>
<tr>
<td>P33</td>
<td>2</td>
<td>17</td>
<td>1</td>
<td>68</td>
<td>M</td>
<td>Mild imprecise articulation; mild hypernasality</td>
</tr>
<tr>
<td>P34</td>
<td>2</td>
<td>36</td>
<td>1</td>
<td>72</td>
<td>F</td>
<td>No significant dysarthria noted</td>
</tr>
<tr>
<td>P35</td>
<td>2</td>
<td>8</td>
<td>1</td>
<td>66</td>
<td>F</td>
<td>Mild breathy voice, consonant imprecision</td>
</tr>
<tr>
<td>P36</td>
<td>2</td>
<td>16</td>
<td>1</td>
<td>84</td>
<td>M</td>
<td>Mild monotone</td>
</tr>
<tr>
<td>P37</td>
<td>2</td>
<td>23</td>
<td>2</td>
<td>72</td>
<td>M</td>
<td>Moderately imprecise articulation</td>
</tr>
<tr>
<td>P38</td>
<td>2</td>
<td>16</td>
<td>1</td>
<td>56</td>
<td>M</td>
<td>Reduced loudness, monotone</td>
</tr>
<tr>
<td>P39</td>
<td>2</td>
<td>17</td>
<td>1</td>
<td>57</td>
<td>M</td>
<td>No significant dysarthria noted</td>
</tr>
<tr>
<td>P40</td>
<td>2.5</td>
<td>25</td>
<td>2</td>
<td>78</td>
<td>M</td>
<td>Moderate hypophonia</td>
</tr>
</tbody>
</table>

Note. For all scales, 0 indicates no clinical impairment, and higher scores are associated with greater degrees of impairment.
**EEG-EMG Procedures**

EEG Ag-AgCl electrodes were placed on the scalp using collodion and filled with an electrolyte gel. The EEG electrode standard 10–20 system positions used were: FP1, FP2, AFz, F7, F3, Fz, F4, F8, FT7, FC5, FC3, FCz, FC4, FC6, FT8, A1, T7, C5, C3, Cz, C4, C6, T8, A2, TP7, CP5, CP3, CPz, CP4, CP6, TP8, P7, P3, Pz, P4, P8, O1, Oz, and O2. An ocular lead to monitor and record eye movements was placed 2 cm under the right lateral canthus. All EEG electrodes were recorded to Fz reference. The right mastoid process was used as ground. Surface EMG Ag-AgCl electrodes were placed on the right and left superior and inferior OO muscles. The EMG electrodes were placed in a bipolar configuration with G1 above the lateral vermilion border of the upper lip and G2 below the lateral vermilion border of the lower lip. All EEG and EMG electrode impedances were < 5.0 kohm. The tonic signal was recorded on a separate channel. The Neuroscan System was used to acquire all EEG and EMG data at 1000 Hz for all participants, with a bandpass of 1–200 Hz.

The superior and inferior OO muscles and their activity related to lip closure and rounding were selected for this study because of their accessibility for surface electrode sampling and because their activation is relatively easy for the experimenter to monitor during the collection of the data. Also importantly, lip closure and rounding are common to both speech and nonspeech tasks and would not necessarily be thought to be more practiced in one task than the other. All speech and nonspeech tasks involved tonic, phasic, or episodic contraction of these OO muscles.

It is recognized that the EMG electrode placement in the present study transduces activation of not only the OO muscles, but other perioral muscles whose fibers interdigitate with them (Blair & Smith, 1986). Further, the bilateral sampling with surface EMG does not permit the independent examination of lip quadrants, which may be subserved by separate motoneuron pools in subnuclei (Goffman & Smith, 1994; Wohльт & Goffman, 1994). However, there is converging and compelling evidence that the lip muscles have a functional synergy for task requirements, which is regulated by a common neural drive (Ito, Gomi, & Honda, 2004; Shaiman & Gracco, 2002; Wohльт, 1996). In this sense, if EEG-EMG coherence is discovered in the present study—and particularly if task-related differences are discovered—the results can be interpreted to reflect the cortical control of task-related functional units or perioral coordinative structures (Kelso, Tuller, & Harris, 1983; Shaiman & Gracco, 2002).

**Tasks**

The tasks were designed to represent a range of motor control requirements, across two nonspeech and four speech tasks collected in 5-min epochs. Each task was performed in three trials in a quasi-randomized order across participants, such that the first task was always a sustained pucker and no task was performed two times in a row. Approximately 20 s of task production was alternated with 20 s of rest throughout the 5-min epochs of data collection. Instructions, demonstration, and practice were provided before the first trial of each task and repeated as necessary throughout the remainder of the session. Participants were instructed to maintain a relaxed jaw, tongue, and forehead between trials to minimize muscle artifact.

**Tonic tasks.** The first task of each session was 20 s of a sustained pucker followed by 20 s of rest through a 5-min period. Participants were instructed to pucker firmly but without strain, to keep the pucker even and steady, and to breathe through the nose. Production requirements included an identifiable activation of OO on the digital EMG display.

The tonic speech task was a sustained “oo” in which participants phonated “oo” for approximately 5 s, followed by 10 s of rest through the 5-min epoch. These data are not included in the present report for two reasons. First, it proved to be a difficult task for both groups of speakers, but more so for the speakers with PD. As a result, there was some modification of task procedures between speakers, and this notwithstanding, there was a great degree of variability in the way in which the individual speakers performed the task. Second, because not all speakers performed this task, the number of epochs available for analysis was different from that of the sustained pucker and would limit comparability of these conditions.

**Phasic tasks.** In the phasic nonspeech task, participants were instructed to alternate lip pucker with lip retraction (pucker-smile) at a rate of approximately 1 cycle/s. Identifiable phasic OO activation was verified on the EMG trace throughout each trial, and participants were given verbal feedback to facilitate a consistent level of activation for each movement.

The phasic speech task was the alternation of the syllables **dee boo** at a rate of approximately 1 syllable/s.3 The demonstration by the examiner was precise and metered but did not exaggerate oral movements. The
demonstration did not include any alteration of fundamental frequency or intensity, and participants who altered these parameters were instructed to make the words sound equal and even. Phasic OO activation was verified on the EMG trace throughout each trial.

**Connected speech.** Two connected speech passages were created specifically for the purposes of this study (see the Appendix). The first poem-like passage (“Green Tea”) consisted of dyads of single-syllable words that alternately required activation of OO, either in lip rounding, protrusion, or closure, in a metered fashion of approximately 1 dyad/s, F1, and F2 values for /i/ and /u/ were measured using the automatic tracking function of TF32 on the spectrographic display. Ten consecutive productions, randomly selected for each speaker, were measured, using standard formant frequency measurement procedures. The purpose of this passage was to extend the phasic OO activation elicited in the pucker-smile and dee boo conditions to real words that centered around a theme. The OO activation envelope elicited by this passage roughly followed a phasic pattern, with the expected variations associated with the production of individual phonemes.

A second passage (“Beach”) also was constructed to contain an abundance of sounds requiring OO activation. However, this passage, which was a brief narrative, was not metered, and participants were instructed to read the sentences in connected phrases at a natural rate (demonstrated at approximately 2 syllables/s to discourage rapid reading), without taking any breaks or pauses. This passage was to represent the most natural discourse-like task, and therefore the nature of OO activation was tied to phonetic constraints rather than to temporal metering.

**Speech Sample Procedures and Analysis**

A Shure microphone was placed on a stand in front of the participant approximately 5 in. from his or her mouth. The speech signal was recorded on a Sony portable digital audiotape (DAT) recorder (PCM-M1) whose output was sent to the Neuroscan system. Because absolute sound pressure level was not a target measure during the signal collection, the microphone distance was adjusted to achieve the optimal acoustic signal on the Neuroscan display and DAT recording and such that offline identification and analysis of speech trials could be made.

Verbal feedback was provided to all participants to ensure compliance with the task instructions, and performance deviations were the basis for epoch exclusion. To verify the perceptual impressions of relative comparability among the tokens for each group, sample measures of speaking rate (syllables per second) for the connected speech tasks and formant frequencies (F1 and F2) for the dee boo task were conducted. One randomly selected trial of each connected speech sample was selected for each speaker. The digital file was displayed as a waveform and spectrogram using TF32 software. Using standard procedures for identifying acoustic onset and offset, the cursor function was used to measure the durations of the first 10 dyads of the Green Tea passage and the first four phrases of the Beach passage; syllables-per-second calculations were conducted to compare group performance. To assess possible differences in vowel production in the dee boo task, F1 and F2 values for /i/ and /u/ were measured using the automatic tracking function of TF32 on the spectrographic display. Summary data were compared between groups, and two-tailed t tests were conducted to determine significant differences (p < .05). Approximately 10% of the samples were remeasured by a second judge for reliability purposes.

**EMG-EEG Analysis**

The data were processed off-line with EMG rectification, referencing to the average of the ear electrodes, and 512-point epochs (511 ms) were created. Each epoch was inspected for the task-appropriate OO activation in conjunction with the acoustic signal. As with any EEG study of speech production or mouth movement, volume conduction from jaw and forehead muscle activation can and does produce EMG artifact in EEG electrodes. In the present study, all epochs that contained visible artifact during the task or during the rest periods were rejected, and the rejection rate was regularly at 50% of epochs. For all tasks, however, it was possible to identify 60–80 high-quality epochs per participant. A computer-generated random selection of 50 epochs for each task per participant was completed. Each selected 50-epoch set for a given task was pooled for all 20 participants within each group, yielding a 1,000-epoch total for each task per group.

Fast Fourier transform (FFT) and coherence analysis were performed using the Neuroscan software with a frequency resolution of 1.957 Hz. Coherence was calculated between all EEG electrodes and right OO as well as between left and right OO up to 200 Hz. Where appropriate, the phase latency in milliseconds was calculated as \( \text{phase angle}/360\times (1,000 \text{ ms/frequency at coherence peak}) \).

Corticomuscular coherence spectra were visually examined to identify patterns within the frequency bands, particularly band peaks, and cortical areas of interest. It should be stated that the frequency bands that have been targeted in investigations of corticomuscular coherence vary considerably from study to study. Without a standard, we chose an 8–50-Hz range to include frequencies easily inclusive of the Piper rhythm (40 Hz) and those that have been shown to be important in moderate- and phasic muscle activation. Moreover, our range...
excludes common tremor frequencies of PD (4–5 Hz and 5–7 Hz for rest and activation tremors, respectively), as tremor was not a focus of the present investigation (Halliday et al., 1998; Salenius et al., 1997). In terms of spatial targets, we focused on coherence spectra referenced to right OO for field distributions that would be characteristic for increased activity over motor areas, that is, either sensorimotor cortex (fronto-central, central, centro-parietal electrodes, or C5) or SMA (midline fronto-central electrodes, or FCz). Coherence spectra referenced to left OO also were examined for the presence of cortical lateralization, and the relevant results of this analysis are presented. Peak coherence values that exceeded the 95% confidence limit lines were regarded as having significant coherence for that frequency band; between-group comparisons of coherence magnitude allowed for the identification of between-group coherence differences for these frequency bands. Peak coherence values that did not exceed the confidence limits were defined as nonsignificant. The difference between coherence estimates that exceed the significance limit can be assessed with general linear statistics, as long as the number of values between or among comparison groups is approximately the same (Mima & Hallet, 1999). This was applied when possible in the form of analysis of variance (ANOVA) and paired t tests. In addition, visual inspection of FFT spectra for the comparisons of interest was conducted, along with targeted phase lag calculations derived from the coherence calculation.

Results

Speaking Rate and Formant Frequency Findings

Interjudge reliability on the acoustic measures was regarded as acceptable, with no syllable duration difference exceeding 20 ms, no F1 difference exceeding 20 Hz, and no F2 difference exceeding 30 Hz for any of the items measured. No original values were modified based on the remeasurements.

Table 2 contains the means and standard deviations for the speaking rate and formant measures for both groups. In general, the PD group members, with their mild hypokinetic dysarthria, exhibited a faster speaking rate in the connected speech passages than the control group. Although statistically significant, these mean differences were less than 1/2 syllable/s for both reading passages and were therefore not regarded as representing profound performance differences in speaking rate. Formant values were highly comparable between the two groups, and the differences did not reach statistical significance. However, the mean F1 and F2 values for PD were slightly centralized relative to those of the control group, as would be expected with a mild dysarthria. The performance measures on this subset of productions support the impression of the experimenters of comparable productions between control and PD group participants.

Coherence Field Distribution Findings

For any task, field distributions demonstrating significant coherence were found only over the sensorimotor cortex region and the fronto-central midline, supporting robust biological relevance of the data for these movement tasks. The sensorimotor cortex field distribution was more prominent with the right OO as the coherence reference. For the left sensorimotor cortex region, the maximal amplitude was at C5, with smaller amplitudes at C3 (medially), lateral fronto-central electrodes (anteri orly), and centro-posterior electrodes (posteriorly). For the fronto-central midline, the maximal amplitude was at FCz with a wide fronto-central field distribution that decreased in all directions from FCz but with a more gradual decrease in midline electrodes. The C5 maximum field distribution corresponds somatopically with the lateral left primary motor strip, and the FCz maximum field distribution corresponds with the SMA. Results

| Table 2. Results of acoustic analysis to determine production similarities between control speakers and those with Parkinson’s disease (PD). |
|----------|----------|----------|----------|----------|
| Dependent variable                  | Control  | PD       |          |
|                                    | M      | SD      | M      | SD      | p value |
| Syllables per second, Green Tea passage | 2.19  | 0.32 | 1.80  | 0.42 | .003* |
| Syllables per second, Beach passage | 3.10  | 0.52 | 3.67  | 0.68 | .03* |
| /i / F1 Hz                          | 290.3 | 34.8 | 306   | 36.8 | .203 |
| /i / F2 Hz                          | 2291.2| 272.6| 2212.2| 260.1| .257 |
| /u / F1 Hz                          | 303.3 | 58.7 | 326.3 | 62.3 | .273 |
| /u / F2 Hz                          | 1067.6| 437.8| 1125.8| 239  | .622 |

*p < .05.
are presented for each of these two electrode locations. The field distribution for the C5 maximum is shown in Figure 1, and that for the FCz is shown in Figure 2.4

The issue of volume conduction contamination of scalp EEG recording deserves special mention as it is a significant and serious impediment to EEG in speech production research. In the present study, all epochs with visible EMG artifact were rejected; however, not all artifact is observable, and even low levels have the potential to contaminate EEG scalp recordings. There are two pieces of evidence that low-level EMG artifact did not induce false significant findings in the present study. The first evidence pertains to the possibility that jaw and scalp muscle activation during speech produced artifact in reference electrodes at the ears. In our study, all EEG electrodes were referenced to average ears, so if EMG contamination was present in the reference electrodes, we would see it at all EEG electrode sites. Figures 1 and 2 show that this is not the case and that the higher coherence has a definite field of distribution and is greatest in the frontal and midline electrodes, consistent with motor strip activation, with less coherence in the posterior electrodes. We would not see this very focal field distribution about the motor regions if significant EMG contamination from the reference electrodes was present. A second possible outcome of low-level EMG artifact is that it may be present disproportionately for one group or the other due to some physiological explanation. For example, did excess volume conduction associated with muscle rigidity in the PD participants obscure or reduce the EEG-EMG coherence, or less likely, enhance coherence in some way? Again, the data show this not to be the case. The variation in the coherence patterns (wherein coherence was higher at C5 for PD than control for sustained pucker but lower than control for all tasks at FCz) would not suggest that one group produced greater EMG artifact than the other in any systematic way. Although the possibility that volume conduction obliterated other significant corticomuscular coherence that may have been present cannot be ruled out, the pattern of results casts doubt that volume conduction artifactually produced or enhanced coherence findings.

**FCz Findings: SMA**

As shown in Figure 3, all tasks elicited significant coherence values in both control and PD groups in the 8–50-Hz band over FCz. The general pattern of coherence showed higher values for the lower frequencies in this band with a decrescendo to 30 Hz. Beyond 30 Hz, the coherence values were much lower and without distinctive peaks. For all tasks, the coherence values for the control group were generally higher than for those of the PD group. In addition, the three speech tasks elicited higher coherence for both groups than did the nonspeech tasks at most frequency buckets between 8 and 30 Hz.

To evaluate the observation that the coherence for the control group was generally higher than for the PD group across all tasks, control and PD coherence values for each frequency bucket from 8–30 Hz (1.95-Hz resolution) were compared across tasks with a paired two-sample t test for means. The 30–50-Hz band was not analyzed because of generally low coherence values for both groups and the absence of distinctive peaks. The t test revealed that the coherence values of the frequency buckets for the control group were significantly greater than that for the PD group across tasks, $t(54) = 8.23, p < .0001$.

The second observation is that, in general, the nonspeech tasks elicited lower coherence values than the
Figure 2. Field distribution of FCz-right-OO coherence maximum distribution for control data. Note the maximum amplitude at FCz across the 8–50-Hz band. Electrode positions are named with standard 10–20 nomenclature. The vertical axis denotes FCz-right-OO coherence values.

Figure 3. FCz-right-OO coherence spectra for each of the five tasks comparing PD (solid line) with control (dashed line). The dotted horizontal line denotes the .003 value of the 95% confidence limit.
speech tasks, and the dee boo condition elicited higher values than did the two reading passages. These impressions were assessed by one-way ANOVA on the significant coherence values of all buckets between 8 and 30 Hz for each task and for each group. Both the ANOVAs for the control and for the PD data were significant, $F(4, 54) = 12.53, p < .0001$ for control; $F(4, 54) = 5.41, p < .0001$ for PD.

Post hoc paired $t$ tests were conducted for each pair of tasks within each group to identify significant differences ($p < .005$ with Bonferroni adjustment for multiple comparisons). These data are presented in Tables 3 and 4. Of the comparisons between the nonspeech versus speech conditions, four of six (67%) were significant for the control group and five of six (83%) were significant for the PD group. Thus, in general, coherence for nonspeech tasks was lower than for speech tasks for both groups. For neither group was there a significant difference between the two nonspeech tasks; however, both groups showed differences in the speech tasks. For the control group, dee boo was of higher coherence than the Green Tea passage (borderline significance), which was of significantly higher coherence than the Beach passage. Differences among the speech conditions for the PD group were less robust, with the Green Tea passage eliciting slightly higher coherence than the dee boo condition. The lack of a clear pattern among speech conditions for the PD group may be a consequence of the relatively low levels of coherence, producing somewhat of a floor effect.

**C5 Findings: Left Sensorimotor Cortex**

Unlike the coherence patterns over FCz, the field distribution with a significant coherence peak over C5 was found only in one task. Figure 4 shows a significant coherence value centered sharply at 23.44 Hz over C5 for the PD group data in sustained pucker. The control group data had a much smaller peak value in the adjacent frequency bin (21.49 Hz) that only slightly exceeded the confidence limit line. No other patterns exhibiting peaks in coherence bands were demonstrated for any other tasks, within either group, or across other electrodes. We then examined the coherence values from individual participants to verify the extent to which the pooled data represented them. We found that 16 of 20 (80%) of the individuals in the PD group but only 4 of 20 (20%) in the control group showed significant coherence at or adjacent to 23.44 Hz. A chi-square analysis revealed that the PD group has a significantly greater rate of exceeding the confidence limit levels than the control group ($p < .001$, 95% confidence interval = 27–82 points).

### OO: Right to Left Coherence

The EMG-EMG coherence between right OO muscles and left OO muscles reached significance for both PD and control groups in the sustained pucker task only. As shown in Figure 5, significance is reached in the 8–50-Hz band with a superimposed prominent peak in the 20–25-Hz band and a smaller one in the 8–12-Hz band. This coherence was greater for the PD group, particularly at the 8–12-Hz and 20–25-Hz bands. The 20–25-Hz band peak also was present in the OO FFT spectra (Figure 5) as well as in the C5 coherence data (Figure 4), strongly supporting the biological significance of this finding.

### Tables

<table>
<thead>
<tr>
<th>Task</th>
<th>Pucker-smile</th>
<th>Sustained pucker</th>
<th>Dee boo</th>
<th>Green Tea passage</th>
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<td>Sustained pucker</td>
<td>.753</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Dee boo</td>
<td>.033</td>
<td>.0013*</td>
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</tr>
<tr>
<td>Beach passage</td>
<td>.0001*</td>
<td>.0001*</td>
<td>.144</td>
<td>.081</td>
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</tbody>
</table>

*p < .005 (Bonferroni correction).
Discussion

This investigation demonstrates that speech and oral nonspeech movements elicit varying degrees and locations of corticomuscular coherence that, when present, converges on the sensorimotor and/or supplementary motor cortices. Moreover, it identifies differences between the corticomuscular coherence patterns in these healthy and PD populations that may reflect the nature of the movement abnormalities in PD.

Control findings. Restricting our discussion first to the findings for the control group, we conclude that significant corticomuscular coherence exists between right OO muscles and the SMA region (electrode FCz) in the 8–50-Hz frequency band for all tasks. Significant corticomuscular coherence in the 8–50-Hz band also was found over the sensorimotor cortex areas (electrode C5); however, this coherence was much smaller than that for the FCz electrode site. The control group exhibited no hemispheric lateralization in either the FCz or C5 field distributions for any of the tasks herein. For FCz, lateralization would not necessarily be an expected finding because of the midline placement of the electrode and the SMA’s output for bilateral muscle activation (Lotze et al., 2000; Murphy et al., 1997). Although there are conflicting reports regarding lateralization of speech and nonspeech oral tasks in the primary motor cortex (see, e.g., Lotze et al., 2000; Murphy et al., 1997; Wildgruber, Ackermann, & Grodd, 2000), this is a theoretically more likely location for identifying lateralization of function. In the present study, the corticomuscular coherence at C5 was significant but small, and this may have hidden any lateralization that actually was present.

Task-related coherence pattern differences were found for both the FCz and C5 electrode sites, but with quite different task patterns. For the C5 distribution, significant coherence was discovered for sustained pucker task, but no defined peaks in the 8–50-Hz band were present for the pucker-smile or for any speech tasks. An opposite trend was found for the FCz data, which included significant coherence for all tasks, with significantly greater coherence for the speech versus nonspeech tasks, and with dee boo coherence greater than the two reading tasks. The functional significance of the two corticomuscular distributions is likely quite different. The sensorimotor cortex (C5) coherence may reflect corticomuscular coupling of frequencies for the purpose of primary muscle activation, whereas the FCz coherence is related to corticomuscular coupling for the sake of producing more complex coordination of muscle activation frequencies. This hypothesis is consistent with the task-specific roles of involvement for these brain regions that have been advanced in time domain studies of functional imaging and electrophysiology (Ackermann & Riecker, 2004; Lotze et al., 2000; Shaiman & Gracco, 2002; Wildgruber et al., 2000; Wohlert, 1993). The SMA is known both to be involved in the generation of complex movement and to have direct corticofugal projections to motor nuclei (Jurgens, 2002; Keizer & Kuypers, 1989). Greater activation of the SMA is seen with more complex tasks, including speech production (Haslinger et al., 2001; Lotze et al., 2000; Murphy et al., 1997; Wildgruber, Kischka, Ackermann, Klose, & Grodd, 1999; Wohlert, 1993).
Coherence abnormalities in PD. The PD group differed from the control group in two ways: elevated coherence at the primary sensorimotor cortex area (C5) for the sustained pucker task, and reduced coherence at the SMA (FCz) for all other tasks. Each of these findings is addressed in turn.

The elevated corticomuscular coherence in PD for sustained pucker suggests increased rhythmic coupling between the sensorimotor cortex pyramidal cell dendritic potentials and OO EMG activities in the frequency domain. Indeed, we found converging evidence that suggests a loss of modulation flexibility that may underlie speech and oral movement abnormalities in PD. The topographical localization of this increased corticomuscular coupling shows peak activity over the contralateral lateral sensorimotor cortex at C5. There was also significant coherence over the ipsilateral hemisphere at C6, but the C5 coherence value was much higher, suggesting left lateralization of this activity. The phase lag in milliseconds for the C5-right-OO electrode pair was 6.8 ms, which is consistent with the latency range obtained by magnetic cortical stimulation of 5–10 ms (Oge et al., 1993; Urban, Beer, & Hopf, 1997). When the coherence was referenced to the left OO, the C5 coherence value was less but still greater than that seen at C6. The control group exhibited small coherence values that only slightly exceeded the confidence limits over C5 or C6 with reference to either OO. It is possible that this apparent lateralization in PD reflects an amplified version of normal patterns. In the literature on limb cortical control in PD, an increased activation of lateral motor areas is thought to represent an attempt at compensation for inadequate involvement of midline motor areas (i.e., SMA) due to understimulation from the basal ganglia output (Brown & Marsden, 1998). At first glance, our data may seem to support such a view with regard to speech. However, the fact that the abnormal EMG activity and corticomuscular coherence appear in narrow frequency bands (20–25 and 8–12 Hz) suggests that this change is dysfunctional rather than functional. A similar argument has been made by Salenius et al. (2002) in limb studies of PD “on” and “off” states with EMG activity and corticomuscular coherence.

EMG-EMG analysis between the OO muscles further supports the conclusion of abnormally increased coupling in the 20–25-Hz and 8–12-Hz frequency bands in PD, indicative of an increased cortical coupling to these muscles at these frequencies. The phase lag in milliseconds for the left-OO-right-OO electrode pair was 0.55 ms, which is inconsistent with transcortical conduction. The phase lag seen here could be explained by neural transit times for bilateral activation when the activation is simultaneous or nearly so.

An FFT analysis provides additional evidence for the possibility of abnormally increased coupling. In the control group, the averaged FFT OO spectrum for sustained pucker showed a broad spectrum of activation with relatively smaller peaks at 8–12 Hz and separately at 20–25 Hz. This is very similar to what has been found for tonic arm muscle activation paradigms (Caviness et al., 2003; Marsden et al., 2000; Raethjen et al., 2002). The sustained pucker FFT OO spectrum for the PD participants was similar to that of control but with overall higher power values and a relatively more prominent peak at around 10 Hz and less prominent peak at 20–25 Hz. The presence of the same 20–25-Hz band peak in both corticomuscular coherence and muscle–muscle coherence in PD supports the view that this excessive coupling is a robust finding and may represent the pathophysiology of abnormal OO muscle control in PD.5

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5To rule out the possibility that a subclinical facial/oral tremor may have produced an artifactual increase in coherence in the PD group, we reexamined our EMG FFT spectra of all participants. Three out of 20 PD participants demonstrated small peaks (~25% of envelope size) at different frequencies, including 9.77, 7.81, and 5.86 Hz. One of 20 control participants had a small peak at 7.81 Hz. The rarity of these relatively small peaks in both groups is of uncertain significance and could not account for the pooled or individual EEG-EMG coherence results.
Further, the observation at 10 Hz is analogous to the increased 10-Hz activity with increased corticomuscular coherence reported for wrist muscular activity in PD (Salenius et al., 2002).

The increased coupling may represent pathological motor unit synchronization, which effectively reduces modulation flexibility and constrains the movement in reaching its spatial and temporal targets. Such a conclusion is consistent with the nature of motor speech deficits observed in the PD population, which are characterized by reduced articulatory excursions, rushing, monotony, and so on (Darley, Aronson, & Brown, 1969). Further, similar findings were reported by Wohlert (1996), in which older women showed more highly coupled EMG activation among lip quadrants in various speech and nonspeech tasks than did their younger counterparts. These results were interpreted as reflecting loss of flexibility in fine oral motor control with increasing age.

The second finding for corticomuscular coherence abnormalities in PD is the relatively reduced levels of coherence at the FCz relative to that of the control group for all tasks. Although the task-specific patterns were similar to those produced by the control group, the magnitude of coherence was reduced. A physiological explanation for this finding is that the abnormal output of the basal ganglia in PD is known to focus on the SMA (Brown & Marsden, 1998; Marsden, Limousin-Dowsen, Ashby, Pollak, & Brown, 2001). The reduced corticomuscular coherence between the SMA and OO may be the consequence of the decreased or abnormal input to the SMA from the basal ganglia in PD. The functional implication is that the SMA does not provide its normal contribution to the oral motor control, including speech production.

In summary, this study suggests at least two mechanisms underlying the pathology related to speech and oral movement production deficits in patients with PD: (a) diminished modulation flexibility linked to the sensorimotor area and (b) reduced corticomuscular coherence at the SMA, possibly reflecting abnormal output of the basal ganglia. It should be restated that these findings emerged despite the fact that the participants with PD exhibited mild dysarthria and were sampled while in the medicated “on” state. It is unknown whether the small but statistically significantly faster speaking rate of the PD participants may have affected the coherence findings. Additional studies to investigate participants with more significant levels of dysarthria in both “on” and “off” medication states will be necessary to fully interpret the present results.

**Conclusion**

Our findings suggest that the organization of speech corticomuscular control may be conceptualized as an orchestra of frequencies that can be used differentially to produce the correct motor programs. Although task specificity was apparent among the corticomuscular coherence patterns, questions remain regarding the aspects of task differences that are meaningful to the nervous system. We have found frequency domain abnormalities in cortical and OO muscle control in PD versus control groups, with certain activation frequencies abnormally increased or decreased. These findings complement techniques using the time domain such as functional imaging and certain neurophysiology techniques to define the mechanisms underlying abnormal control of speech production in PD.

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Appendix. Connected speech passages.

“Green Tea”
Green tea, blue moon. Steamed tea, cool moon.
Peach trees in view. Three trees for you.
Sweet peach, gold juice. Eat peach, so true.
Green tea, hot brew. Steep tea for you.
Clean streets, not new. Steal treats, wind blew.

“Beach”
We watched purple waves crash upon the beach, as strong, balmy breezes blew westward. Palm trees bent with each burst of wind, warning people of the approaching storm.
Analysis of High-Frequency Electroencephalographic-Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson's Disease

John N. Caviness, Julie M. Liss, Charles Adler, and Virgilio Evidente

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