Voice and Fluency Changes as a Function of Speech Task and Deep Brain Stimulation

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Purpose: Speaking, which naturally occurs in different modes or "tasks" such as conversation and repetition, relies on intact basal ganglia nuclei. Recent studies suggest that voice and fluency parameters are differentially affected by speech task. In this study, the authors examine the effects of subcortical functionality on voice and fluency, comparing measures obtained from spontaneous and matched repeated speech samples.

Method: Subjects with Parkinson's disease who were being treated with bilateral deep brain stimulation (DBS) of the subthalamic nuclei were tested with stimulators ON and OFF.

Results: The study found that a voice measure, harmonic to noise ratio, is improved in repetition and in the DBS-ON condition and that dysfluencies are more plentiful in conversation with little or variable influence of DBS condition.

Conclusions: These findings suggest that voice and fluency are differentially affected by DBS treatment and that task conditions, interacting with subcortical functionality, influence motor speech performance.

KEY WORDS: motor speech disorders, deep brain stimulation, speech tasks, voice, Parkinson's disease

The ability to speak clearly involves a complex brain system that is not fully understood. *Parkinson's disease* (PD), a disorder primarily affecting the basal ganglia, interferes with this ability. In earlier times, subcortical nuclei were regarded as subordinately relaying commands from motor and supplementary motor cortex to lower motor neurons. Intensive studies in the past several decades (DeLong & Georgopoulous, 1981; DeLong, Georgopoulos, & Crutcher, 1983) and the influential lecture by Marsden (1982) have led to a more complex view. The intricacies of motor control by the human basal ganglia have been revealed using several approaches to the question (Utter & Basso, 2008), including neurophysiological (Parent & Hazrati, 1995a), computational (Gurney, Prescott, & Redgrave, 2001a, 2001b), and functional (Eidelberg, 2007) neuroimaging methods.

Several kinds of control and management are now recognized as inherent to basal ganglia processing, including planning and execution (Beneke, Rothwell, Dick, Day, & Marsden, 1987; Brooks, 1996; Watson & Montgomery, 2006), initiation (Atchison, Thompson, Frackowiak, & Marsden, 1993; Burleigh, Norak, Nutt, & Obeso, 1997; Gracco & Abbs, 1987), and monitoring of movements (Cummings, 1993; Gassler, 1978; Taylor & Saint-Cyr, 1992). Recent approaches to the basal ganglia describe

it playing a central role in behavioral "action selection" (Gurney et al., 2001a, p. 401). In Baev's (1995) model of basal ganglia function, monitoring is achieved in the dopaminergic system through matching of the predicted gesture with the actual afferent flow coming from the executed motor gesture. Thus, far from constituting an indirect pathway, circuitry in the basal ganglia forms an "additional integrative station" enabling motor gestures in concert with widespread projections to other subcortical and to cortical neurons (Parent & Hazrati, 1995b, p. 128). In a similar view, Graybiel (1998) proposes that the basal ganglia formulate representations of motor and cognitive action sequences in order to implement them as performance units.

These interpretations of basal ganglia function drawn from motor control studies have important implications for our understanding of speech motor control. Poor coordination of speech gestures in hypokinetic dysarthria may be attributable to impaired motor planning as well as defective ongoing monitoring (Connor, Abbs, Cole, & Gracco, 1989; Gracco & Abbs, 1987). Speech disorders in basal ganglia disease may arise in part from deficient execution and maintenance of an appropriate internal model of the action plan (Georgiou et al., 1993; Gurney et al., 2001a). The dysarthria associated with basal ganglia disease is characterized by imprecise articulation; changes in rate and rhythm; and soft, breathy vocal quality, which often seriously interferes with intelligibility (Canter, 1963, 1965a, 1965b; Darley, Aronson, & Brown, 1975; Forrest, Weismer, & Turner, 1989). These characteristics are found in varying combinations and to varying degrees in PD, a disease in which inadequate production of dopamine negatively affects the complex network of inhibition and excitation relations among subcortical nuclei.

Parkinsonian speech disorder, called *hypokinetic dysarthria,* arises as a combination of deficient respiration, phonation, articulation, resonance, and prosody (Goberman & Coelho, 2002). Hypokinetic dysarthria was commonly held to manifest consistently across talking of any kind (Duffy, 1995, p. 62; Shames & Wiig, 1990; Yorkston, Beukelman, & Bell, 1988), not influenced by linguistic variables, such as complexity or lexical frequency, or task effects, such as reading versus spontaneous speech. However, contemporary models of the basal ganglia are consistent with the notion that specific vocal tasks might be expected to place different demands on processing and, therefore, might be differentially affected by disease.

As an instructive example of task effects, it is well known that singing, a vocal mode similar to speech, is associated with reduction of dysfluencies in chronic stuttering (Ludlow & Loucks, 2003). In cases of severe nonfluent aphasia, singing of a familiar melody (Yamadori, Osumi, Masuhara, & Okubo, 1977) with and without familiar lyrics (Hébert, Racette, Gagnon, & Peretz, 2003) may be preserved, and singing improves intelligibility in some of the dysarthrias (Hughlings Jackson, 1874; Kempler & Van Lancker, 2002). Similarly, specific task demands have been used to induce fluency in stutterers (Andrews, Howie, Dozsa, & Guitar, 1982). External cues, such as a metronome or choral speech support, often provide a dramatic benefit to dysfluent speech (Alm, 2004). Task effects on vocal disability in spasmodic dysphonia have also been reported (Roy, Gouse, Mauszycki, Merrill, & Smith, 2005).

The study reported here arises from clinical observations as well as previous reports that compromise to basal ganglia competence affects articulatory and phonatory success for spontaneous and repeated speech quite differently. One of the important differences between these two speech modes may well be that although spontaneous speech requires the generation of an internal motor plan followed by initiation, execution, and monitoring, an external template is provided for repeated speech, thus reducing the burden on motor speech control throughout the process.

The use of deep brain stimulation (DBS) of the subthalamic nucleus to treat PD provides a reversible means of modifying the activity of the basal ganglia. Although effective in reducing nonspeech motor symptoms, this form of therapy has no effect or even a negative effect on speech (Tripoli et al., 2008; Wang, Verhagen Metman, Bakay, Arzbaecher, & Bernard, 2003). Some parallels exist with levadopa therapy, which has a variable effect on motor activation (Feigin et al., 2002), and gains from the pharmacological intervention are not as significant for speech as they are for limb function (Dromey, Kumar, Lang, & Lozano, 2000). These facts raise questions about the relationship between speech and nonspeech motor control in PD and, more generally, about the nature of cortical–subcortical interactions during speech.

Our general aim is to better understand cortical–subcortical interactions in normal and dysarthric speech as well as the role of such interactions in specific dimensions of speech production. To study the effects of DBS on cerebral control of speech, this portion of the larger project focused on voice quality and articulatory fluency, using acoustic measures obtained in two types of motor speech task: conversation and repetition. We tested repetition in two contexts. The first context was *conversation repetition,* which is defined as the repetition of phrases excerpted from the subject's spontaneous conversation. This enabled a direct comparison of spontaneous and repetition modes using the same phrases. The second context was the repetition of specific statements and questions presented by the examiner and performed twice, mirroring the conversation, and conversation repetition conditions.

The first and second sentence repetitions provided an estimate of a practice effect that might occur in the conversation repetition condition.

Method
Subjects

Seven right-handed, male speakers of American English with PD, ages 49–62 years (*M* = 58 years) and with 14–18 years of education (*M* = 16.1 years), volunteered for the study. They had received the diagnosis of idiopathic PD between 9 and 16 years of age (*M* = 11.9 years) before inclusion in this study and were between two and 56 months (*M* = 21 months) post DBS programming (see Table 1). Subjects were otherwise healthy and had no significant psychiatric or medical disorders. For treatment of tremor and rigidity, they received bilateral electrodes surgically implanted in the subthalamic nuclei. Motor function improved with DBS therapy (see Table 1). Pre- and postsurgical speech testing was not performed, but there were no indications of microlesion effects in these subjects prior to DBS programming. Subjects provided self-evaluations about their speech during the course of their time with PD, including any changes following DBS surgery. During the presurgical period, three subjects reported no speech problems, whereas four subjects indicated that their speech became softer, and two subjects reported having experienced dysfluencies. Following initiation of DBS therapy, three subjects reported that their speech became worse, one subject reported an improvement, and three subjects reported having experienced no change in speech.

Informal clinical evaluation of conversational speech by a speech-language pathologist at time of testing prior to turning off DBS indicated that five of the seven subjects had evidence of dysfluencies or hesitations, six subjects had impaired voice quality (soft, breathy, or strangled), and three subjects showed articulatory imprecision (see Table 2).

All subjects were free of Parkinsonian medication for at least 12 hr when they provided speech samples in both the DBS-ON and the DBS-OFF conditions, which were conducted at least 1 week apart. Testing in the DBS-OFF condition occurred at least 2 hr after turning off the stimulators. This protocol was approved by the Institutional Review Board of the Nathan Kline Institute for Psychiatric Research, and all subjects provided written informed consent.

Speech samples. Speech samples were recorded using a head-worn microphone (Shure) and a Marantz digital recorder. Tasks chosen for this study were conversation, conversation repetition, and sentence repetition (performed twice to mirror the conversation/conversation repetition tasks). These measures were obtained by first eliciting a 5-min sample of conversational speech, during which the subject discussed a hobby, family vacation, or other topic of his or her choice at the beginning of the speech examination. From this audio recorded corpus, 30 phrases and sentences were excerpted from the subject's conversation for a repetition task. These excerpted speech samples were complete linguistic units of three to seven words, free of slang, specialty and low-frequency vocabulary, or proper nouns. Approximately 30 min later, the subject was instructed to repeat the excerpted phrases and sentences, taken from his original spontaneous

Table 1. Demographic information for study subjects.

SID	AGE	ED	PD duration	DBS duration	Levodopa	UPDRS–III OFF	UPDRS–III ON	H & Y OFF	H & Y ON
104	57	16	16	27	400	56.5	55.5	5.0	4.0
106	59	15	10	9	600	27.5	19.0	2.5	2.5
107	62	18	15	2	600	26.0	24.0	2.5	2.0
108	61	14	11	12	600	27.0	9.0	2.0	2.0
109	49	16	9	4	300	23.5	21.5	2.5	2.0
110	62	16	11	56	600	52.5	31.0	4.0	3.0
111	56	18	11	37	400	10.5	4.0	2.0	2.0
M (SD)	58.0 (4.6)	16.1 (1.5)	11.9 (2.6)	21.0 (20)	500 (129)	31.9 (16.5)	23.4 (16.8)	2.9 (1.1)	2.5 (0.8)

Note. SID = subject identifier; AGE = age in years; ED = education in years; PD duration = time (in years) since diagnosis of Parkinson's disease; DBS duration = number of months since activation of deep brain stimulation. Levodopa refers to the daily dose in milligrams. The Unified Parkinson's Disease Rating Scale (UPDRS–III) motor score (Fahn et al., 1987) and the Hoehn and Yahr (H & Y) disease staging scores (Hoehn & Yahr, 1967) are presented for the DBS-ON and DBS-OFF examinations. Both the UPDRS–III, *t*(6) = 2.74, *p* = .034, and the H & Y, *t*(6) = 2.52; *p* = .045, scores demonstrate significant improvements with DBS-ON. The bottom row provides group means (*M*s) and standard deviations (*SD*s).

Table 2. Subjects' self-report of speech changes associated with DBS therapy and the clinical impression at study intake.

SID	Speech history	Pre-DBS speech	Post-DBS speech	Clinical impression
104	None	Clear, fluent	Difficulty with word formation, speech initiation, low voice, mumbling, stuttering, lower pitch, dysfluent, spells out loud when speech freezes	Short rushes, freezing, dysfluent, strangled voice, aphonic
106	None	Soft voice, difficulty with word formation not readily noticeable	Mumbling for 4–5 months, stuttering for 8 months	Slurring, soft voice variable rate, dysfluent
107	Mild stuttering until age 21	Stammering, soft voice, poor intelligibility	Improved	Some imprecision, uneven loudness, fast rate, dysfluent, breathy voice
108	None	Fine	No change	Somewhat soft voice
109	Articulation therapy, elementary through high school	Soft speech	Mild dysfluency, pronouncing words not quite so fluid	Mild slurring, mild hesitation
110	None	Soft, hesitant speech	Good initially, soft and hesitant later	Soft voice, slowed, hesitation, word-finding difficulties, flat prosody
111	None	Soft speech	Speech stronger	Some slurring, soft voice

conversation. This enabled the analysis and comparison of identical forms of speech samples under two different task conditions. In order to estimate the extent to which a practice effect might contribute to differences between conversation and conversation repetition, a sentence repetition task was performed twice during a comparable time interval. In this task, subjects repeated four statements and four questions at the behest of the examiner. Any differences in acoustic measures taken from these first and second sets of eight sentence repetitions could then be compared with differences obtained from the conversation and conversation repetition tasks.

Speech data. For this study, speech was characterized in terms of voice quality and fluency. To examine voice quality, harmonic-to-noise ratios (HNR) were obtained for vowels in the conversation, conversation repetition, and first and second sentence repetition samples using Praat software (Boersma & Weenink, 2009). The HNR values were normalized (nHNR) using the durations of the measured vowel portions. The normalization for each segment was a multiplier calculated as a ratio obtained by dividing the longest duration across segments in all conditions by the duration of each segment. This normalized the HNR values across short and long segments in the different conditions.

Dysfluencies were narrowly defined as the difference between the number of target syllables in an utterance and the number of syllables actually produced. Dysfluencies were quantified from the wave form by (a) determining the difference between the number of target syllables and the number of syllables actually produced and (b) expressing the difference as a percentage of the number of target syllables.
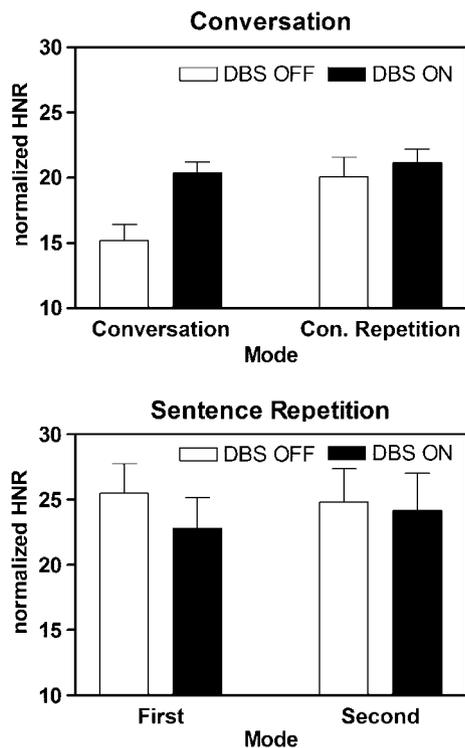
Results
Subject Characteristics

Subject characteristics examined in relation to the acoustic measures were age, education, duration of DBS, and duration of disease (time since PD diagnosis). Neither age nor education values were correlated with any of the production measures. However, significant negative correlations were found between nHNR and the duration of DBS in the DBS-ON condition for the first, $r = -.95$, $p = .001$, and second, $r = -.89$, $p = .007$, sentence repetitions, such that nHNR decreased for the sentence repetition task as the duration of DBS therapy increased over months. Disease duration was positively correlated with dysfluencies during conversation in both the DBS-ON, $r = .85$, $p = .016$, and DBS-OFF, $r = .88$, $p = .009$, conditions, such that the proportion of dysfluencies during conversation increased with disease duration. A similar relationship was observed for conversation repetition only in the DBS-OFF condition, $r = .80$, $p = .03$.

Voice Quality

The nHNR values were analyzed using repeated measures analysis of variance (ANOVA). The factors were Task
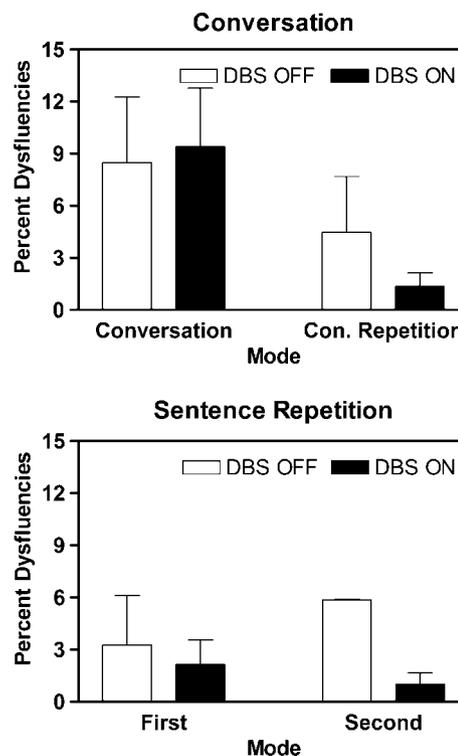
Figure 1. Average harmonic-to-noise ratio (HNR) values for speech produced during spontaneous conversation and conversation repetition as well as during the first- and second-sentence repetitions in the DBS-OFF and DBS-ON conditions. The normalized HNR (nHNR) values were normalized for the duration of the measured segment. Higher values represent higher nHNR. DBS = deep brain stimulation. Error bars represent standard error of the mean.

Figure 2. Mean number of dysfluencies measured in speech produced during spontaneous conversation and the repetition of utterances produced during conversation (conversation repetition) and the first and second repetitions. Both tasks were performed in the DBS-OFF and DBS-ON states. The number of dysfluencies represents the difference between the number of target syllables in the utterance and the actual number of syllables produced. This number is then expressed as a percentage of the total syllables produced. Higher values represent greater percentages of dysfluencies.

(conversation, sentence), DBS (OFF, ON), and Repetition (conversation and conversation repetition, first and second sentence repetition). The results are depicted in Figure 1. There was a significant effect of Task, $F(1, 6) = 8.05$, $p = .03$, with a higher nHNR for sentence repetition than for conversation. There was also a Task × Repetition interaction, $F(1, 6) = 10.05$, $p = .019$, with a significant increase in nHNR between conversation and conversation repetition but not between the first and second sentence repetitions. Finally, there was a significant Task × Repetition × DBS interaction, $F(1, 6) = 7.23$, $p = .036$, with a significant increase in nHNR during conversation with DBS-ON but no DBS effect during conversation repetition or the first or second sentence repetitions.

An examination of the pairwise differences in conditions provides an estimate of the relative effects of DBS, Repetition, and Task on nHNR. The difference in nHNR during conversation in the DBS-OFF and DBS-ON conditions revealed a 34% increase with DBS-ON, $t(6) = -2.97$, $p = .025$. The effects of Repetition were evaluated in the DBS-OFF conditions. The improvement in nHNR between conversation and conversation repetition was

32.1%, $t(6) = -2.79$, $p = .032$. In contrast, the improvement in nHNR between conversation and first sentence repetition was 67.8%, $t(6) = -3.59$, $p = .009$.

Fluency

Because of the differences in the occurrences of dysfluencies in the conversation and sentence repetition tasks, these tasks were analyzed separately. For conversation, there was a significant reduction in the percentage of dysfluencies during conversation repetition compared with conversation, $F(1, 6) = 7.86$, $p = .031$. There was no significant effect of DBS. For sentence repetition, there were no significant effects of first and second repetition or of DBS.

As with nHNR, an examination of pairwise differences in the DBS-OFF condition provided an estimate of the effects of repetition and task on dysfluencies. There were 90.2% more dysfluencies in conversation than in conversation repetition, $t(6) = 4.03$, $p = .007$. There were

158% more dysfluencies in conversation than in the first sentence repetition, $t(6) = 3.07$, $p = .022$.

Discussion

The present results demonstrate that the effects of task, DBS, and subject characteristics (duration of DBS and disease) interact with specific measures of speech. For voice quality, nHNR was 32% higher when conversational material was repeated than when it was originally spoken. There was a comparable 34% improvement in nHNR during conversation when DBS-ON was compared with DBS-OFF. There were no comparable nHNR effects when the first and second repetitions of sentences were compared. However, there was an influence of DBS on nHNR across subjects during sentence repetition in that nHNR decreased with duration of DBS therapy over months in the DBS-ON condition. With the relatively high nHNR during sentence repetition, this appears to be a subtle effect during the natural history or course of DBS therapy and PD.

Just as a subject effect on nHNR for DBS-ON was observed in the condition with the highest nHNR, a subject effect for dysfluency was observed in the condition with the highest percentage of dysfluency. In the conversation condition, the percentage of dysfluencies increased with disease duration in both the DBS-ON and DBS-OFF conditions. For conversation repetition, this relationship was observed only in the DBS-OFF condition, suggesting that DBS does have an effect on dysfluencies under some task conditions. Task was the major factor in the fluency measure, with a reduction in dysfluencies when conversational material was repeated compared with when it was originally produced. In the DBS-OFF condition, there was a 90.2% reduction for repetition in the percentage of dysfluencies. There were no significant main effects or interactions with DBS in the fluency measure in group performance, although dysfluencies were more than doubled in the DBS-ON condition in two of the subjects.

Finally, as the effect of task was a major focus of this study, performances during conversation and the first sentence repetition were compared in the DBS-OFF condition. For voice quality, nHNR was 67.8% higher during sentence repetition than during conversation. The task difference in percentage of dysfluencies was greater, with 158% greater percentage of dysfluencies during conversation.

Our results show that fluency and phonation were not uniformly affected by task or by DBS state. In the case of voice quality, the effect of task appears to be comparable to the effect of DBS in improving HNR. An improvement in acoustic measures for voice using a repetition task during DBS-ON has been reported elsewhere (Gentil, Chauvin, Pinto, Pollak, & Benabid, 2001). Worsened speech following DBS was reported particularly for the spontaneous mode of speaking (Rousseax et al., 2004). In our results, fluency was less affected by DBS state than was phonation on these tasks. Speech was less fluent in conversation than in either repetition condition (conversation repetition or sentence repetition). With respect to fluency, the effect of task is much larger than the effect of DBS. However, it should be noted that dysfluency was narrowly defined in this study. Examinations of rate and pausing are in progress.

Our findings of less-than-dramatic changes in speech in association with DBS-ON and DBS-OFF find correspondence in the current literature. Reports of speech changes are inconsistent and variable and appear to involve small differences. The differential effects of DBS on the elements of speech become apparent in recent summary reports (Tripoli et al., 2008; Krack et al., 2003). Dromey et al. (2000) found only small changes in vocal fundamental frequency (F0) and amplitude in seven subjects who had undergone DBS treatment. The Dromey et al. article is relevant in several respects. They found a task effect with increased F0 during conversation but not with sustained phonation. Further, this increase was found only when subjects were receiving both DBS and levodopa. D'Alatri et al. (2008) reported that subthalamic nucleus DBS produced more stable glottal vibration with reduced frequency and amplitude tremor, which was not associated with an improvement in speech performance.

Role of Task Factors

Certain effects of task conditions on speech effectiveness have previously been reported. Through the use of intelligibility measures, differences have been seen for spontaneous speech versus reading or repetition. In a study of accelerated speech following bilateral thalamic surgery in a patient with PD, Canter and Van Lancker (1985) observed a task effect in the patient's intelligibility. Speech samples read aloud by this patient were more intelligible than samples of the patient's spontaneous speech. Similarly, a comparison of sentences from the Assessment of Intelligibility of Dysarthric Speech (Yorkston & Beukelman, 1981) with spontaneous speech obtained from dysarthric subjects revealed, again, that dysarthric speakers were more intelligible when reading aloud (Frearson, 1985). In both of these studies, different speech samples were used for the comparison tasks. A later study of a single PD patient with severe dysarthria revealed a 50% decrease in intelligibility for spontaneous speech exemplars when compared with the same speech exemplars in reading and repetition (Kempler & Van Lancker, 2002).

Acoustic differences as a function of speech task also appear in the literature as early as 1943, when differences in pitch and duration were observed for reading and

"impromptu speaking" (Snidecor, 1943, p. 50). Schulz, Greer, and Friedman (2004) studied task effects on speech production in PD subjects who had undergone pallidotomy surgery. Measures of sentence duration, pause duration, and frequency of pauses differed for reading, picture description, and conversation. These authors suggested that picture description and conversation, as spontaneous tasks, may place a greater burden on the vocal system than reading. Brown and Docherty (1995) compared several acoustic parameters in dysarthric speakers of variable etiology while they read a paragraph versus spoke spontaneously. The reading condition was associated with longer vowel durations in some subjects but not in those with PD. The PD subjects showed a different speech task effect—longer voice onset times in reading. Kent, Kent, Rosenbek, Vorperian, and Weismer (1997) compared repetition with conversational speech in individuals with cerebellar ataxia. The dysarthric speakers produced longer syllable durations than the control group in sentence repetition but not in conversation. Acoustic differences were also found in the single case of dysarthria reported by Kempler and Van Lancker (2002) using blind rating of spectrograms. Formant structures on spectrograms were noisier and more incoherent on speech examplars spontaneously produced than on the same exemplars in read and repeated task modes, and this measure—a visual representation of signal-to-noise ratio—correlated with intelligibility ratings.

Kent and Kent (2000) developed profiles of the different type of dysarthrias, comparing sustained vowel phonation, diadochokinesis, and conversational speech tasks. In subjects with hypokinetic dysarthria in PD, vowel prolongation revealed greater F0 and first formant variability than in subjects with normal speech. Prosodic irregularities that are usually present in dysarthria were highlighted in conversation but less so in the rote tasks. Other researchers have noted that the relative rankings of deviant perceptual characteristics are not the same in syllable repetition as in reading for individuals with dysarthria (Zeplin & Kent, 1996). These reports, although somewhat fragmentary, suggest that motor speech characteristics vary—in some cases, consistently—with task.

The influence of task on speech observed in this study may be attributable to the lack of an external model in conversation versus the presence of an external model in repetition. These findings for speech are in agreement with numerous observations of other motor behaviors. PD subjects have been described as "enormously disadvantaged" by lack of internal cues (Georgiou et al., 1993, p. 1575). "Gait ignition failure" is commonly seen clinically in subjects with PD; taking a step is aided by an external stimulus (Atchison et al., 1993; Burleigh et al., 1997) such as a hockey stick or a line on the floor. The subcortical systems performance circuit proposed by Baev (1995, p. 38) contains a "model of the controlled object," implying that a deficient subcortical system will falter when an internal model is required, as in conversational speech. Studies have demonstrated that motor deficits in PD are more severe in internally guided than in externally guided motor tasks using reaching gestures (Lewis et al., 2007; Schenk, Baur, Steude, & Bötzel, 2003).

Research in the field of stuttering also suggests a task-dependent motor speech system (Alm, 2004), which may involve basal ganglia mechanisms. The speech of people who stutter has been known to improve when provided with an external cue in the form of rhythmic support. The insufficiently organized system supporting spontaneous speech can be, in part, bypassed in a condition where external support is provided.

DBS and Levadopa Effects

Comparisons can reasonably be made with studies of levodopa, as neurologists anticipate that the effects of DBS in the ON state on motor function will be comparable to an optimal dose of levodopa (Marks, 2009; Okun, 2009). As mentioned previously, the effects of levodopa on speech are variable (Wolfe, Garvin, Bacon, & Waldrop, 1975). De Letter, Santens, and Van Borsel (2005) observed improved intelligibility scores using Yorkston and Beukelman's (1981) Assessment of Intelligibility of Dysarthric Speech, which utilizes reading and repetition. In numerous studies, various speech parameters show no effect or a negative effect of the medication. In a study measuring dysfluencies in PD subjects on and off levodopa in reading and producing a monologue, a significant group effect was not found, but increases in dysfluencies in individual speakers suggested a role of increased dopamine levels in the brain (Goberman & Blomgren, 2003). Similarly, Rousseax et al. (2004) reported articulation difficulties in two of seven subjects in the DBS-ON state. We found a two-fold elevated proportion of dysfluencies in two subjects (29%) in the DBS-ON state (in conversation). De Letter, Santens, de Bodt, Boon, and Van Boersel (2006) reported increased rate variability in 25 individuals with PD in a reading task after levodopa administration, which may have been related to more dysfluencies. In another DBS subject, DBS treatment improved oral control over what had occurred during levodopa treatment (Gentil, Tournier, Pollak, & Benabid, 1999), and greater lip mobility following DBS surgery was observed (Rousseaux et al., 2004).

Several factors may account for the higher HNRs, reflecting a stronger acoustic signal arising from improved voice quality, in DBS-ON. These factors include increased respiratory function, higher subglottal air pressure, and increased air flow over the glottis; firmer and more stable vocal folds; and improved and more consistent control of muscles of the larynx and vocal tract. De Letter, Santens,

De Bodt, et al. (2007) reported improved respiratory measures following levodopa administration in all of the 25 PD subjects tested. A single case study reported improved respiration and phonation time in the DBS-ON condition (Hoffman-Ruddy, Schulz, Vitek, & Evatt, 2001), and longer phonation time was seen in a group of seven DBS subjects (Rousseaux et al., 2004). Levodopa was observed to upscale the overall levels of vocal amplitude and tempo (Ho, Bradshaw, & Iansek, 2008), presumably benefiting from enhanced respiratory function. Pitch and loudness variability improved with medication in 10 subjects (De Letter, Santens, Estercam, et al., 2007). Recent studies of coordination of breath and phonation using intraoral pressure measures revealed improved function for both levodopa and DBS conditions (Sarr et al., 2009). Several voice measures in 20 PD subjects improved with levodopa, and the tremor intensity measure decreased (Sanabria et al., 2001). Positive effects of DBS and of levodopa on phonatory capacity in seven subjects were reported by Sung and colleagues (2004) and in 20 subjects evaluated for pitch (Gentil et al., 2001). In a study of 19 DBS-treated subjects, speech was rated by the treating physicians, speech-language pathologists, and subjects themselves as worse during DBS-ON, but glottal tremor was reduced and phonation time increased (Klostermann et al., 2008), again suggesting a selective improvement in phonation. As noted previously, D'Alatri et al. (2008) reported reductions in both frequency and amplitude tremor with DBS.

Summary

The significant influence of task on motor speech measures in the present study has implications for the study of motor speech. It is clear—from results such as these and results of other studies reviewed here—that task must be taken into account to describe motor speech processes and to understand the effects of brain dysfunction on articulation and voice. It follows that efforts to understand the effects of DBS on motor speech competence must carefully consider task demands when evaluation and treatment are undertaken. These findings further suggest that DBS may affect different components of motor speech processes in different or even opposite ways. It appeared from this study that in the DBS-ON state, voice characteristics were improved, yielding higher HNR values. This occurred during conversation, the condition in which nHNR was lowest in the untreated state. The effect on dysfluencies is less straightforward due to the strong influence of task. It is likely that the nonuniform effects of DBS on elements of motor speech, compounded by the fact that speech performance varies with task, may account in part for the variable reports by individuals with PD of the impact of DBS on their speech.

These results may lead to more specific and empirical questions about the causal relationships between subcortical nuclei and separable components of the motor speech process. Components of speech production are widely understood to be differentially controlled (Murdoch, 2001). The distribution of management of these elements across cortical and subcortical systems is a topic of active research for articulation (Sidtis, Strother, & Rottenberg, 2003; Sidtis, Gomez, Naoum, Strother, & Rottenberg, 2006; Ackermann & Riecker, 2004; Hillis et al., 2004) and voice (Loucks, Poletto, Simonyan, Reynolds, & Ludlow, 2007; Ludlow, 2005; Simonyan & Jürgens, 2003). Further, reflecting the differences in task demands, patterns of brain activity likely differ during externally versus internally guided tasks (Lewis, Slagle, Smith, et al., 2007; Sidtis, Tagliati, Sidtis, Dhawan, & Eidelberg, 2009). Compounding the difficulties in understanding the breakdown of a complex control system in PD and its alteration with DBS is evidence that the progression of PD is the result of neuropathology that progresses by encroaching on a series of brain structures based on their neurobiological properties rather than simply increased destruction in a restricted neuroanatomical region (Braak et al., 2006). This raises the possibility that different aspects of motor speech control in PD are associated with changes in different neurotransmitter systems (Goberman, 2005).

This is a preliminary study in which seven subjects have been carefully evaluated as part of a broader study that includes other tasks, other measures, and functional neuroimaging aimed at better understanding the nature and consequences of cortical–subcortical interactions during speech. Better understanding of the sequelae of surgical treatment can lead to better informed explication of risks and benefits and to enlightened postsurgical counseling. Knowledge of which components of the motor speech function are more or less affected, negatively or positively, will assist in treatment planning for postsurgical PD patients.

Acknowledgments

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