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Research report

Sensorimotor control of vocal pitch and formant frequencies in Parkinson's disease

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ABSTRACT

Background: Auditory feedback reflects information on multiple speech parameters including fundamental frequency (pitch) and formant properties. Inducing auditory errors in these acoustic parameters during speech production has been used to examine the manner in which auditory feedback is integrated with ongoing speech motor processes. This integration has been shown to be impaired in disorders such as Parkinson's disease (PD), in which individuals exhibit difficulty adjusting to altered sensory-motor relationships. The current investigation examines whether such sensorimotor impairments affect fundamental frequency and formant parameters of speech differentially.
Methods: We employed a sensorimotor compensation paradigm to investigate the mechanisms underlying the control of vocal pitch and formant parameters. Individuals with PD and age-matched controls prolonged a speech vowel in the context of a word while the fundamental or first formant frequency of their auditory feedback was altered unexpectedly on random trials, using two magnitudes of perturbation.
Results: Compared with age-matched controls, individuals with PD exhibited a larger compensatory response to fundamental frequency perturbations, in particular in response to the smaller magnitude alteration. In contrast, the group with PD showed reduced compensation to first formant frequency perturbations.
Conclusions: The results demonstrate that the neural processing impairment of PD differentially affects the processing of auditory feedback for the control of fundamental and formant frequency. The heightened modulation of fundamental frequency in response to auditory perturbations may reflect a change in sensory weighting due to somatosensory deficits associated with the larynx, while the reduced ability to modulate vowel formants may result from impaired activation of the oral articulatory musculature.

1. Introduction

Parkinson's disease (PD) is a multisystem disorder associated with a range of motor and sensory deficits. In PD, the speech motor symptoms of hypokinetic dysarthria include both laryngeal deficits and articulatory impairments (Ackermann et al., 1997; Caligiuri, 1989; Connor et al., 1989). Laryngeal deficits such as reduced F0 variability are among the clearest symptoms (Skodda et al., 2009). Articulatory abnormalities include a reduction in the vowel space, characterized by the lowering of high frequency formants and the elevation of low frequency formants (Skodda et al., 2012). It has been suggested that this acoustic restriction results from limited movements of the articulators, notably the tongue and jaw (Skodda et al., 2012). Sensory deficits for speech include impairments in auditory processing of voice and speech (Ho et al., 2000; Ackermann et al., 1997; Gräber et al., 2002).

PD also affects sensorimotor processing for speech with most studies focused on the ability of individuals with PD to integrate auditory feedback with speech motor control processes. Auditory feedback during speech production provides information on the control of multiple speech actions, including the principal vibratory characteristics of the larynx (fundamental frequency, or F0) and the shape of the vocal tract through the resonant (formant) properties. Changes in F0 primarily signal suprasegmental (i.e., intonational) properties (Möbius and Dogil, 2002) and are known to be sensitive to rapid, moment-to-moment auditory feedback modulations in healthy participants (Burnett et al., 1998;

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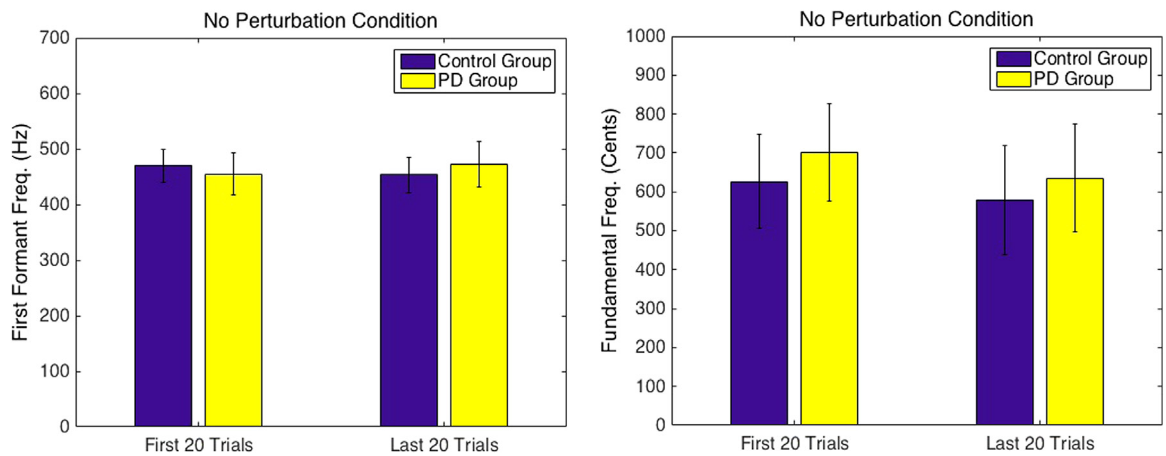

Fig. 1. No perturbation conditions: The mean first formant (F1) frequency (left) and the mean fundamental (F0) frequency (right) in Hertz for the first and last 20 trials productions of the target vowel /ε/ for the PD and Control subjects.

Larson et al., 2000), whereas formant properties are primarily associated with segmental (i.e., phonemic) distinctions, in particular for vowels and vowel-like consonants. The control of segmental parameters is typically less sensitive to sudden changes in auditory feedback, with compensatory changes occurring more slowly, and to a lesser degree, than for suprasegmental parameters (Perkell et al., 2000). Nonetheless, it has been demonstrated that during the course of a single production, talkers will compensate for an induced perturbation in pitch or formant structure by altering speech output in the direction opposite to the perturbation (Purcell and Munhall, 2006; Tourville et al., 2008; Burnett et al., 1998).

Previous investigations have shown that individuals with PD exhibit complex speech production responses to such manipulations that depend on the specific feedback parameter being manipulated (Chen et al., 2013; Liu et al., 2012; Mollaei et al., 2013). When auditory feedback is altered, a motor response is typically observed in the direction opposite to the shift. The manipulation can be predictable, used to evaluate error-based learning, or unpredictable, used to assess online sensorimotor control. For unpredictable shifts in F0, individuals with PD have been shown to respond with a *larger* compensatory response than individuals without PD (Chen et al., 2013; Liu et al., 2012). In contrast, for predictable formant frequency changes, individuals with PD have been found to respond with a *reduced* adaptation response compared to healthy individuals (Mollaei et al., 2013). The contradictory findings suggest that auditory feedback control of F0 and formant properties may be differentially impaired in PD, giving rise to different compensatory patterns. However, it is difficult to directly compare the results of prior studies examining these different acoustic parameters, as they have been investigated under different speech motor control tasks (online control versus error-based sensorimotor learning).

Here, we investigated the compensatory responses in individuals with PD and healthy control participants to unpredictable, real-time perturbations in F0 and first formant frequency (F1) during vowel production. Participants were instructed to repeatedly produce and sustain the vowel [ε] in the embedded word “head”. Two blocks of auditory feedback perturbations, one with fundamental frequency perturbation condition and the other with first formant frequency perturbation condition, were used to alter participants' auditory feedback. Each manipulation condition consisted of two magnitudes and lasted for the whole duration of the trial (for more details see Section 4.3). To ensure that participants did not learn and adapt to the unpredictable auditory feedback manipulations, we compared the average of the first and the last 20 trials between and across the two groups. As noted above, it has been previously found that during the course of a single trial, healthy control participants compensate for an induced perturbation in F0 or F1 by altering speech output in the direction opposite to the perturbation (Purcell and Munhall, 2006; Tourville et al., 2008; Larson et al., 2000; Burnett et al., 1998).

Based on previous findings, we hypothesized that individuals with PD would display a different pattern of compensatory responses from control participants, and further, that different response patterns would emerge for F0 and F1 in individuals with PD. Based on previous research, we expect individuals with PD to show an increased response to F0 manipulations and a reduced response to F1 manipulations. If confirmed in the same group of subjects, these findings would suggest two different dissociable patterns in the manner in which acoustic parameters are processed and integrated during speech in individuals with PD.

2. Results

The average F0 and F1 between the first and last 20 non-perturbed trials in each of the two perturbation conditions (F0 and F1) was compared to ensure that no adaptation as a result of the intervening perturbation was present (see Fig. 1). No statistically reliable differences were observed between the first and last trials for either group (PD group F0: $t[28]=-0.32$, $p=0.28$; PD group F1: $t[28]=-0.37$, $p=0.26$, Control group F0: $t[28]=-0.24$, $p=0.31$; Control group F1: $t[28]=0.48$, $p=0.24$). In addition, we did not observe any differences between groups for the first and the last 20 trials of F0 or F1 (F0 first 20 trials: $t[28]=0.43$, $p=0.23$; F0 last 20 trials: $t[28]=0.33$, $p=0.29$; F1 first 20 trials: $t[28]=-0.27$, $p=0.36$; F1 last 20 trials: $t[28]=0.26$, $p=0.37$).

2.1. Fundamental frequency perturbation

For perturbations in F0, both the individuals with PD and control participants exhibited compensatory changes in production in the direction opposite to the feedback manipulation (Fig. 2). However, overall, the group with PD showed a greater degree of compensation compared to the control participants. A linear mixed-effects model was fitted to the averages of the compensatory responses with *time* (every 10 ms, totaling 40 time points over 400 ms) and *magnitude* (small vs. large perturbation) as the within-subject factors, and *group* (PD vs. control) as a between-subjects factor. Significant main effects of time ($F[39, 2160]=10.52$, $p<0.01$), magnitude ($F[1, 2160]=21.16$, $p<0.01$),