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Research Article

The Relationship Between Speech Perceptual Discrimination and Speech Production in Parkinson's Disease

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Purpose: We recently demonstrated that individuals with Parkinson's disease (PD) respond differentially to specific altered auditory feedback parameters during speech production. Participants with PD respond more robustly to pitch and less robustly to formant manipulations compared to control participants. In this study, we investigated whether differences in perceptual processing may in part underlie these compensatory differences in speech production.

Methods: Pitch and formant feedback manipulations were presented under 2 conditions: production and listening. In the production condition, 15 participants with PD and 15 age- and gender-matched healthy control participants judged whether their own speech output was manipulated in real time. During the listening task, participants judged whether paired tokens of their previously recorded speech samples were the same or different.

Results: Under listening, 1st formant manipulation discrimination was significantly reduced for the PD group compared to the control group. There was a trend toward better discrimination of pitch in the PD group, but the group difference was not significant. Under the production condition, the ability of participants with PD to identify pitch manipulations was greater than that of the controls.

Conclusion: The findings suggest perceptual processing differences associated with acoustic parameters of fundamental frequency and 1st formant perturbations in PD. These findings extend our previous results, indicating that different patterns of compensation to pitch and 1st formant shifts may reflect a combination of sensory and motor mechanisms that are differentially influenced by basal ganglia dysfunction.

Approximately 90% of individuals with PD experience speech and auditory processing disorders (Duffy, 2013). The speech disorder of PD, hypokinetic dysarthria, consists of disturbances in prosody, phonation, and articulation (Duffy, 2013). Phonatory and laryngeal deficits are among the most common speech disturbances of hypokinetic dysarthria, and while reduced loudness is the most prominent laryngeal symptom, reduced fundamental frequency (f0) and monopitch are also among the cardinal disturbances of speech (Duffy, 2013; Skodda, Rinsche, & Schlegel, 2009; Skodda, Visser, & Schlegel, 2011a, 2011b). The articulation deficits in PD include a restriction of vowel formant frequencies and imprecise consonants (Duffy, 2013; Roy, Nissen, Dromey, & Sapir, 2009; Skodda, Grönheit, & Schlegel, 2012). It has been argued that speech disorders in PD are not solely motor in nature but also have sensory and perceptual components (Arnold, Gehrig, Gispert, Seifried, & Kell, 2014; Chen et al., 2013; Liu, Wang, Metman, & Larson, 2012; Mollaei, Shiller, Baum, & Gracco, 2016). For example, in a functional magnetic resonance imaging study, Arnold et al. (2014) found reduced activation associated with monitoring of auditory feedback. They suggested that this reduced monitoring might underlie inaccurate updating of motor representations that manifest in dysarthria.

In addition, it has been found that individuals with PD are not able to correctly scale their speech output in the absence of any external cue, although they are able to do so under explicit instructions (Clark, Adams, Dykstra, Moodie, & Jog, 2014; Fox & Ramig, 1997; Ho, Bradshaw, & Iansek, 2000; Kwan & Whitehill, 2011). These internal

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self-correction deficits suggest that difficulties in the monitoring of speech production might be related to the way auditory information is being perceived. This deficit would be consistent with reduced levels of attention during speech perception in PD (Brown & Marsden, 1988). However, little is known about sensory processing related to speech production in PD. To investigate the sensory contributions to speech production, real-time perturbations of auditory feedback can be used to evaluate error-based corrections. This requires processing the error and correcting for it. The perturbations can be predictable, known as sensorimotor *adaptation,* or unpredictable, used to assess the online sensorimotor control process, known as sensorimotor *compensation*. Healthy speakers correct their speech output by compensating for perceived auditory feedback alterations (Larson, Burnett, Kiran, & Hain, 2000; Purcell & Munhall, 2006; Tourville, Reilly, & Guenther, 2008). In PD, individuals exhibit differences in their ability to correct for auditory feedback errors, as shown using both compensation and adaptation paradigms, reflecting a deficit in integrating the error signal with a change in motor output (Abur, Lester-Smith, et al., 2018; Chen et al., 2013; Huang et al., 2016; Liu et al., 2012; Mollaei et al., 2016; Mollaei, Shiller, & Gracco, 2013). However, not all studies have found different patterns in PD relative to controls. For example, Kiran and Larson (2001) did not find any differences in the magnitude of the response using a pitch-altered auditory feedback compensation paradigm in individuals with PD; nonetheless, they did find differences in temporal aspects of the response. It should also be noted that they tested individuals with PD on medication (within 2 hr of medication intake), while Liu et al. (2012), Chen et al. (2013), Huang et al. (2016), and Mollaei et al. (2016) tested individuals off medication for at least 12 hr. These differences may account for the inconsistent patterns of results.

Speech production involves multiple subsystems, most notably laryngeal and articulatory, and while these two subsystems function together, they also can be tuned and modulated independently (Liu, Auger, & Larson, 2010; MacDonald, Purcell, & Munhall, 2011). These two subsystems have been shown to be differentially susceptible to real-time manipulations of sensory feedback (Larson et al., 2000; Purcell & Munhall, 2006). f0 and loudness are suprasegmental laryngeal parameters in English and appear to be more sensitive to moment-to-moment changes in auditory feedback (Larson et al., 2000), and they tend to change rapidly with a change in hearing status (Perkell et al., 1997; Svirsky, Lane, Perkell, & Wozniak, 1992), suggesting that they are controlled independently or at least differentially from supralaryngeal articulatory parameters, which exhibit different patterns. Formant frequencies, including first formant frequency (F_1), are mainly a reflection of movement of the tongue shaping the vocal tract and contribute to the quality of a given vowel. F_1 has been shown to be less sensitive than f0 to rapid changes in auditory feedback, with compensatory changes occurring more slowly (Cowie & Douglas-Cowie, 1992; Perkell et al., 2000). In addition, the laryngeal disturbances associated with PD seem to have a different timeline compared to articulatory deficits (Ho, Iansek, Marigliani, Bradshaw, & Gates, 1999; Skodda et al., 2012). Based on these findings and the independence of articulatory and laryngeal features of speech, we hypothesized a different pattern of processing of f0 and F_1 in PD.

Different acoustic properties of speech encode information associated with these different speech motor subsystems. A number of studies have found increased f0 compensation for pitch shifts in PD (Chen et al., 2013; Huang et al., 2016; Liu et al., 2012; Mollaei et al., 2016). Using electroencephalogram testing, Huang et al. (2016) reported larger P2 responses associated with increased compensation of pitch in individuals with PD compared to control participants during vocalization. This larger response was left-lateralized in the superior and inferior frontal gyrus, premotor cortex, inferior parietal lobule, and superior temporal gyrus. Presumably, the enhanced electroencephalogram response is consistent with increased sensitivity to f0 changes and/or increased weighting of auditory information for pitch control. In our previous study (Mollaei et al., 2016), we observed that individuals with PD compensate differently for changes in f0 compared to their response to changes in F_1 during vowel production. Interestingly, participants with PD responded more robustly than controls to pitch perturbations (cf. Chen et al., 2013; Liu et al., 2012), while they responded less robustly to F_1 perturbations. Based on our previous work, it appears that PD may affect the underlying sensorimotor mechanisms for laryngeal and articulatory subsystems differentially. The source (sensory, motor, sensorimotor) of this differential effect is the main focus of this study.

There are a few studies that have investigated speech perception in PD during passive listening tasks (Abur, Lupiani, Hickox, Shinn-Cunningham, & Stepp, 2018; Clark et al., 2014; De Keyser et al., 2016; Dromey & Adams, 2000; Huang et al., 2016; Troche, Troche, Berkowitz, Grossman, & Reilly, 2012). Troche et al. (2012) reported reduced discrimination of frequency and amplitude of pure tones, and Clark et al. (2014) found decreased sensitivity to differences in speech loudness during listening using a magnitude estimation task. However, other studies reported no speech perception deficits during listening in PD (Abur, Lupiani, et al., 2018; Dromey & Adams, 2000; Huang et al., 2016). For example, Abur, Lupiani, et al. (2018) found no group differences in loudness perception for pure tones using a rating scale. These contradictory findings might be explained by the nature of the auditory information under investigation (i.e., pitch and loudness of speech sounds vs. pure tones) and differences in the tasks used (i.e., discrimination vs. magnitude estimation).

While the abovementioned studies investigated perceptual deficits in PD, the focus has primarily been on loudness (Abur, Lupiani, et al., 2018; Brajot, Shiller, & Gracco, 2016; Clark et al., 2014; De Keyser et al., 2016; Ho et al., 2000), lexical (discourse) level attributes

(McNamara, Obler, Au, Durso, & Albert, 1992), and auditory perception of pure-tone differences (Abur, Lupiani, et al., 2018; Troche et al., 2012) rather than at a level of acoustic attributes associated with laryngeal and articulatory control. Here, we focus on two aspects of perceptual processing for both laryngeal and articulatory changes: the ability to monitor feedback changes during production and the more general ability to detect differences in pitch and formant manipulations during listening. These two perceptual processes are different in that self-monitoring after production requires comparison of feedback with an internal representation of the intended production (Niziolek, Nagarajan, & Houde, 2013), while auditory discrimination is an ability to recognize differences between sounds during listening that may not engage internal representations of the sound. It has been found that cortical and subcortical structures involved in self-monitoring during production and listening are distinct (Behroozmand et al., 2015).

In this study, we investigated the ability of participants with PD to self-monitor and detect changes in f0 and F_1 parameters during speech production and perception and compared these abilities to their sensorimotor compensatory responses. In keeping with the finding of increased pitch compensation (Chen et al., 2013; Huang et al., 2016; Liu et al., 2012; Mollaei et al., 2016), we hypothesized that participants with PD would be better able to detect pitch errors compared to control participants during production. Similarly, in line with the finding of reduced compensation to F_1 alterations found in our previous studies (Mollaei et al., 2016, 2013), we predicted that participants with PD would show a reduced ability to detect F_1 errors during production. During listening, we hypothesized a perceptual processing deficit in PD that would result in differences in the ability to detect errors in f0 and F_1 between the two groups. Such an outcome would indicate a deficit in PD that is separable from motor dysfunction. Teasing apart sensorimotor versus perceptual deficits in PD is an important first step in understanding the mechanisms involved in speech monitoring in PD.

Method

Ethics Statement

This study was approved by the McGill Faculty of Medicine Institutional Review Board, in accordance with principles expressed in the Declaration of Helsinki. Informed written consent was obtained from participants prior to their involvement in the project.

Participants

Fifteen participants with PD (six women, nine men; $M_{\text{age}} = 65.87$ years) and 15 age- and gender-matched control participants (six women, nine men; $M_{\text{age}} = 61.58$ years) were recruited for this study. These are the same participants who participated in our previous study (Mollaei et al., 2016). The severity of PD motor symptoms, which we assessed using the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS; Part III, Motor Examination), ranged from mild (a score of 13) to moderate (a score of 48; $M \pm SD$ score = 24.79 ± 9.19; Fahn, Elton, & UPDRS Committee, 1987). The MDS-UPDRS administrator received in-house training at the Speech Motor Control Laboratory at McGill University. Cognitive functioning was assessed using the Montreal Cognitive Assessment (Nasreddine et al., 2005) and was in the normal range for all participants with PD and healthy controls (scores > 26). All participants with PD were taking L-dopa but were tested off medication (12 hr). Two participants with PD had a history of speech therapy that focused on enhancing loudness and intelligibility.

Participants underwent an audiometric screening and were found to have binaural pure-tone hearing thresholds of 40 dB HL or less at 250, 500, 1000, 2000, and 4000 Hz. We included participants with mild hearing loss because the basis of our comparison was between healthy age- and gender-matched control participants and participants with PD, and both groups showed mild hearing loss (as in our previous study, Mollaei et al., 2016). All participants were native speakers of North American English. None used hearing aids or had any other neurological disease or surgical intervention, such as deep brain stimulation, pallidotomy, or thalamotomy.

A standard speech reading assessment (Rainbow Passage; Fairbanks, 1960) was used to rate 43 perceptual characteristics related to the phonatory (e.g., loudness and pitch), articulatory, resonatory, prosodic, and respiratory characteristics of speech. A licensed speech-language pathologist listened to the speech samples of each participant and rated the speech on each characteristic using a 7-point scale (1 = *normal speech* and 7 = *severe speech deviation*), as described in the original reports by Darley, Aronson, and Brown (1969) and 43 perceptual dimensions classification system expanded by Duffy (2013). We used this method to characterize the subtypes of dysarthria and the severity of speech disturbances in each individual with PD and to correlate the severity of dysarthria with error detection responses. The hypokinetic dysarthria subtype was found in participants with PD, with severity ratings of moderate (two participants), mild–moderate (four participants), mild (six participants), and within normal range (three participants). A second rater evaluated the same sample of speech. Interrater reliability was assessed using intraclass correlation (ICC) in order to assess consistency in the ratings of speech perceptual characteristics in individuals with PD. The resulting ICC was in the excellent range, ICC = .90 (Cicchetti, 1994), indicating that the raters had a high degree of agreement. The MDS-UPDRS and perceptual scores (presented in Table 1) were used to assess any relationship between severity of motor and speech symptoms with their speech perceptual ability.

Stimuli and Experimental Design

The study consisted of two separate experiments, each involving the manipulation of f0 and F_1. In the first

Table 1. Individual scores of participants with Parkinson's disease (PD) on the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) and dysarthria perceptual rating.

Participant	MDS-UPDRS	Respiration	Phonation	Resonance	Articulation	Prosody	Total speech score
PD01	15	4	26	3	7	13	53
PD02	25	4	23	3	7	21	58
PD03	31	2	16	4	9	15	46
PD04	24	2	29	3	11	22	67
PD05	33	3	32	3	11	21	70
PD06	5	3	22	3	9	13	50
PD07	23	3	29	3	14	22	71
PD08	48	3	25	3	13	22	66
PD09	27	2	23	4	14	16	59
PD10	13	3	22	3	10	18	56
PD11	22	3	25	5	12	20	65
PD12	3	2	16	4	8	15	45
PD13	22	2	28	3	10	18	61
PD14	33	3	20	3	10	18	54
PD15	38	2	16	3	7	14	42

experiment (production: f0 and production: F_1), participants repeatedly produced the target vowel [ɛ] in the context of the word "head" ([hɛd]), and after each production trial, they had to indicate whether the sound of their own voice (presented in near real time over headphones) was the same or different from what they had produced. For the f0 manipulation condition, 180 trials were carried out, with half of the trials involving a manipulation of feedback (30 trials at each of three magnitudes: small, medium, and large; see below for details). For the F_1 manipulation condition, 120 trials were produced, with half involving a feedback manipulation (30 trials at each of two magnitudes: small and large; see below for details). Altogether, 90 f0 perturbation trials and 60 F_1 perturbation trials were acquired, yielding 150 perturbation trials in total for each participant. In order to assess any potential compensation associated with the f0 or F_1 manipulations, participants were instructed to sustain the vocalic portion of the utterance for 2.5 s. The choice of the stimulus and its duration was consistent with our previous study (Mollaei et al., 2016), and while it may be somewhat different from typical word production, our main aim was the comparison between the two participant groups. In the production experiment (Experiment 1), the perturbed trials were quasirandomized with the constraint that two shifted trials of the same magnitude would not occur consecutively.

In the second experiment (listening: f0 and listening: F_1), participants listened to pairs of prerecorded samples of their own speech recorded during the first experiment and completed an auditory discrimination task (AX paradigm, with a "same" or "different" judgment following each presented pair of stimuli) using the same manipulations and magnitudes of feedback error induced in f0 and F_1. As in Experiment 1, the second experiment included 300 trials in total, 150 of which involved a perturbation, with 90 "different" trials involving f0 perturbations, 60 "different" trials involving F_1 perturbations, and 150 "same" trials, hence counterbalancing the number of same versus different trials. Participants were instructed to make same/different judgments as quickly and accurately as possible for each presented pair of words. We chose this design because it is suitable for exploring perceptual accuracy based on the changes that arise during speech production (Macmillan & Creelman, 2005). The order of stimulus presentation and alteration magnitude was randomized. At the level of an individual trial (each consisting of a pair of words), the interstimulus interval was 400 ms in order to reduce the auditory memory load of task in participants with PD and older healthy controls (Troche et al., 2012). The duration of the stimuli in the listening task was the same as that in the production task and equal to 2.5 s. The loudness of each stimulus in the listening task was adjusted based on each participant's production, amplified to a volume of 70 dB SPL to be consistent with the production task. Each pair of stimuli was normalized to ensure equal loudness and duration.

For both experiments, participants were first tested under one shift condition (f0 or F_1 shift), followed by a short rest period (approximately 10 min), and then tested under the second condition. The order of manipulation conditions was counterbalanced among participants. f0 was manipulated in an increasing direction, because it has been previously shown that this perturbation elicits a significantly larger response magnitude compared with a reduction in f0 (Chen et al., 2013). The manipulation of F_1 was also in an increasing direction (in the direction of [ɛ] to [æ] in the vowel space), in line with our previous study using a vowel formant adaptation paradigm (Mollaei et al., 2013).

Manipulation of Auditory Feedback

The participants' voices were transduced using a head-mounted microphone (C520, AKG) that was located 20 cm from participants' mouths. The microphone signal was digitized at 22,050 Hz/16-bit (Fast Track Pro, M-Audio) and was recorded on a PC using MATLAB (The MathWorks, Inc.). In parallel with the recording, the acoustical signal was processed in near real time using a VoiceOne vocal processor (TC Helicon) and played back to participants through circumaural headphones (880 Pro, Beyerdynamic).

For the shifting of F_1, the speech processing involved pre-amplification of the microphone signal and then splitting of the line-level signal into two channels. In one channel, the VoiceOne was used to shift all formant frequencies by 15% or 30% (depending on the condition), after which the signal was analog low-pass filtered (Model 751A, Rockland) in order to isolate the F_1 (using a cutoff frequency of 1100 for males and 1350 for females). A second channel consisting of an unaltered speech signal (no formant shift) was high-pass filtered using the same cutoff frequency and then mixed with the low-pass formant shifted signal, thereby creating a full-spectrum speech signal with only the F_1 altered. The full-spectrum speech signal was then mixed with pink masking noise and amplified once again prior to presentation over headphones. The total processing delay of the system was 11 ms, regardless of shift magnitude.

For the shifting of f0, the VoiceOne processor was used to alter the line-level (pre-amplified) microphone signal with no additional filtering. The altered speech signal was then mixed with pink masking noise prior to the final amplification and presentation to the participant. The feedback delay in the f0 shifting condition was 9 ms, regardless of shift magnitude.

Under conditions of large f0 perturbation, the Digital Signal Processor increased the f0 by 100 cents (1 semitone); for the medium perturbation, f0 was increased by 50 cents (0.5 semitone); and for the small perturbation, f0 was increased by 25 cents (0.25 semitone). For the large formant perturbation, F_1 was increased by 30% (averaging 135.1 Hz); for the small formant perturbation, F_1 was increased by 15% (averaging 47.5 Hz). In PD, different magnitudes of f0 and F_1 perturbations have been used, and it has been shown that the response to auditory perturbations is not linear (Chen et al., 2013; Liu et al., 2012; Mollaei et al., 2016). Here, in order to be consistent with our previous study, we chose the same magnitudes of F_1 manipulation, and for f0, the medium and large perturbations were similar to our previous study (Mollaei et al., 2016). However, we added a small-magnitude condition (25 cents) to the f0 manipulation based on our pilot testing to hinder any ceiling effect during the auditory discrimination task. The perturbations were measured in cents for f0 because cents are used to express small intervals, and it has been found that healthy adults are capable of recognizing pitch differences as small as 25 cents (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967).

In both perturbation conditions (f0 and F_1), the feedback alteration started at the beginning of each trial and lasted for the duration of the trial. The altered speech signal was amplified and presented to participants at a volume of approximately 70 dB SPL (e.g., Mollaei et al., 2016, 2013). In order to reduce subjects' perception of their unmodified air- and bone-conducted speech signal, the subjects' altered speech signal was mixed with 60 dB SPL of pink masking noise. For the listening condition (Experiment 2), we induced the same magnitude of perturbations to prerecorded samples of speech of the participants, mixed the speech signal with 60 dB SPL of pink masking noise, and presented it back to the participants during the auditory discrimination task.

Procedure

The microphone was placed at a fixed distance of 20 cm from the mouth. Word production was cued by the presentation of the target word on a computer screen. Participants were instructed to produce the target word "head" that contained the target vowel [ɛ], to prolong the vowel for the duration of 2.5 s (guided by the visual presentation of the word on screen), and then to indicate their judgment. Each stimulus was presented for 2.5 s followed by a 1.5-s interstimulus interval. Participants were asked to begin speaking immediately upon the visual presentation of the target word.

During a practice/setup period (20 trials), participants were asked to produce the target word at a comfortable speaking volume, at which point the microphone gain level was adjusted such that the pre-amplified signal level sent to the vocal processor was close to a known level (i.e., amplification was reduced for relatively loud talkers and increased for soft talkers). This adjustment yielded a resultant output speech signal of approximately 70 dB SPL at the headphones. This was critical to maintain a known speech level relative to the 60–dB SPL pink masking noise. Along with the individually adjusted microphone gain, a digital VU meter was calibrated for each subject in order to present a visual target to the participant that corresponded to the 70–dB SPL speech signal level. This VU meter, which was always visible at one edge of the computer monitor directly in front of the subject, presented the desired speech level (± 3 dB) as a green-colored target zone. Participants were instructed to maintain their speech level within this zone to the best of their ability, with the experimenter providing verbal feedback (to speak louder or softer) if the level was observed to drift away from the target over several trials. This method has been used in multiple previous studies in both healthy control participants and individuals with PD (Huang et al., 2019; Mollaei et al., 2016, 2013; Rochet-Capellan & Ostry, 2011; Shum, Shiller, Baum, & Gracco, 2011).

After each word production, a question appeared on the computer screen—"Same or different?"—to which participants had to respond by indicating on the computer keyboard whether what they heard was the same or different from what they produced. During the listening experiment, participants listened to two speech tokens played one after another and then saw the question on the screen —"Same or different?"—to which they responded by pressing the appropriate response key on the computer keyboard. Participants were not instructed to listen to any particular acoustic feature but rather to simply indicate if the two sounds were different in any way.

Data Analysis

For the production trials, data from the first 400 ms of each vowel production were included in the averaging. For f0-perturbed trials, an autocorrelation method (Zahorian & Hu, 2008) was used to estimate f0 over a series of overlapping 25-ms windows of the speech signal (increments of 10 ms). The f0 values in hertz were then converted to the cent scale using the formula: cents = 100 × (39.86 × log10 [0/reference]), where reference = 195.997 Hz (the note G-3; Chen et al., 2013). For the F_1-manipulated trials, the F_1 in the vowel productions in the shifted feedback conditions was identified using a custom-written script in MATLAB (and Signal Processing Toolbox, The MathWorks, Inc.) to carry out linear predictive coding (LPC) acoustic analysis. In extensive prior testing, the software routine was found to provide results highly comparable to that of the LPC-based formant analysis in Praat (Burg algorithm) for the same LPC order, pre-emphasis, and windowing parameters. The analysis was performed on overlapping 20-ms windows of the speech signal in increments of 4 ms. Formant estimates for each trial were visually inspected for clearly erroneous values. When the initial formant estimation was a poor fit, the LPC order was manually adjusted to improve the stability of the resulting estimates. The F_1 trajectory was aligned from the time of the vowel onset and was averaged across trials frame by frame for each condition.

For the measurement of f0 compensation, the magnitude of the vocal response in each perturbation trial was measured as the difference in f0 (at each 10-ms increment) between the perturbed trial and the immediately preceding, nonperturbed trial. The measurement of F_1 compensation in each perturbation trial was measured as the difference in F_1 (at each 4-ms increment) between the perturbed trial and the immediately preceding, nonperturbed (baseline) trial. The mean f0 and F_1 compensation traces for each participant, representing the mean change from baseline, were then averaged across participants in each group. Discrimination responses were analyzed in terms of participants' accuracy in detecting the variations in the manipulated signal in the same/different judgment task based on the manipulation type and magnitude by calculating the sensitivity index (d') for each participant and then averaging across participants for each condition. d' scores for each participant were calculated by subtracting the z-transform of the hit rate (proportion of stimuli correctly identified as different) from the false alarm rate (proportion of stimuli incorrectly judged as different when they were in fact the same) in order to account for chance guessing (Wickens, 2002).

Statistical analyses were performed using mixed-factorial analyses of variance (ANOVAs) with magnitude (small, medium, and large for f0 or small and large for F_1) and task (production and listening) as within-subject factors and group (PD and healthy controls) as a between-subjects factor on the compensation and d' scores for f0 and F_1 separately. Specifically, we were interested in the differences in error detection abilities between individuals with PD and age-matched control participants, as well as the differences between production and listening tasks in these two groups. Factor and simple effect sizes were quantified using partial η^2 (Witte & Witte, 2010) and Pearson's r (Rosnow & Rosenthal, 1996) based on the amount of variance accounted for by the mixed-factorial ANOVA. Greenhouse–Geisser corrections for unequal variance were applied where warranted. Pearson correlation analyses were carried out between error detection responses (d' scores) for f0 or F_1 across magnitudes for each task and perceptual or clinical rating of severity of PD to investigate the relationship between f0 or F_1 error detection ability and perceptual or MDS-UPDRS clinical scores in individuals with PD. This resulted in eight correlation analyses. A Bonferroni-adjusted α rate of .006 was used.

In addition, separate Pearson correlation analyses were performed between compensation responses of f0 or F_1 and error detection responses (d' scores in pitch or formant) to investigate the relationship between error correction and detection abilities of individuals with PD. This resulted in 10 correlation analyses. A Bonferroni-adjusted α rate of .005 was used.

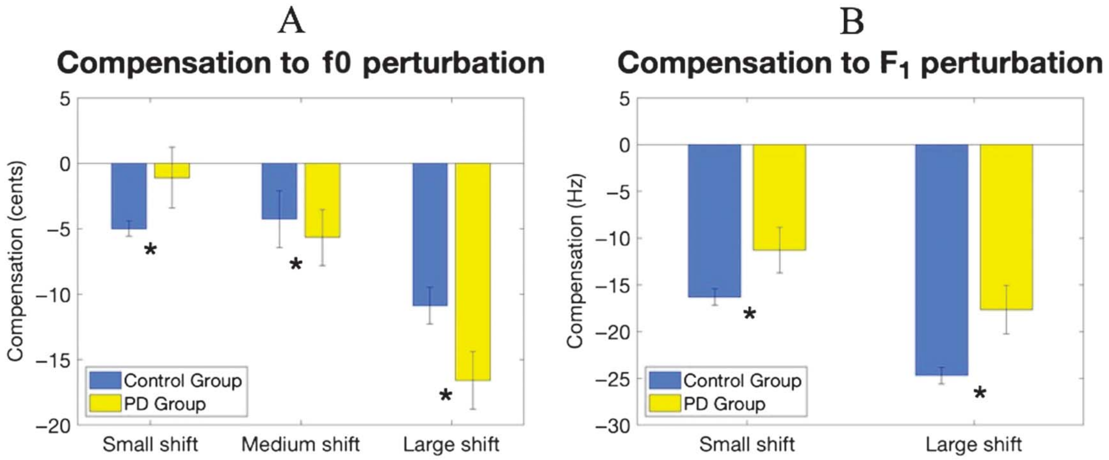
Results

Experiment 1: Production

For f0, both PD and control groups exhibited a compensatory decrease, opposing the feedback manipulation. The effects of group (PD vs. control) and magnitude (small, medium, and large) on f0 compensation were evaluated with a two-way ANOVA. Mean f0 values of the last 100 ms of each vowel at the three shift magnitudes are shown in Figure 1A. A significant main effect of magnitude, $F(1.52, 38.07) = 6.96$, $p < .01$, partial $\eta^2 = .22$, and a significant main effect of group, $F(1, 28) = 9.09$, $p < .01$, partial $\eta^2 = .24$, were found. The two-way interaction was also significant, $F(1.52, 38.07) = 12.91$, $p < .05$, partial $\eta^2 = .34$. Post hoc simple effects analyses were carried out to examine the difference between groups for each magnitude separately. There was a significant difference between the two groups for the medium-magnitude, $F(1.52, 38.07) = 3.03$, $p < .01$, $r = .27$, and large-magnitude perturbations, $F(1.52, 38.07) = 5.65$, $p < .01$, $r = .36$), with the PD group showing a larger compensatory response. The PD group's response to the small-magnitude perturbation was significantly reduced compared to the control group, $F(1.52, 38.07) = −4.67$, $p < .01$, $r = .33$.

For F_1, the two groups responded to the F_1 increase with a compensatory decrease in F_1 output. The effects of group (PD vs. control) and magnitude (small vs. large) on F_1 compensation were evaluated with a two-way ANOVA. Mean F_1 values of the last 100 ms of each vowel at the two magnitudes are shown in Figure 1B. A significant main effect of magnitude (with the large shift showing a greater change than the small shift), $F(1, 28) = 11.53$, $p < .01$, partial $\eta^2 = .29$, and a significant main effect of group (with

Figure 1. (A) Compensation to fundamental frequency (f0) perturbation with three magnitudes (small: 25 cents, medium: 50 cents, large: 100 cents) in individuals with Parkinson's disease (PD; yellow) and control participants (blue). (B) Compensation to first formant frequency (F_1) perturbation with two magnitudes (small: 47.5 Hz, large: 135.1 Hz) in individuals with PD (yellow) and control participants (blue). Error bars show the standard deviation. *$p < .01$.

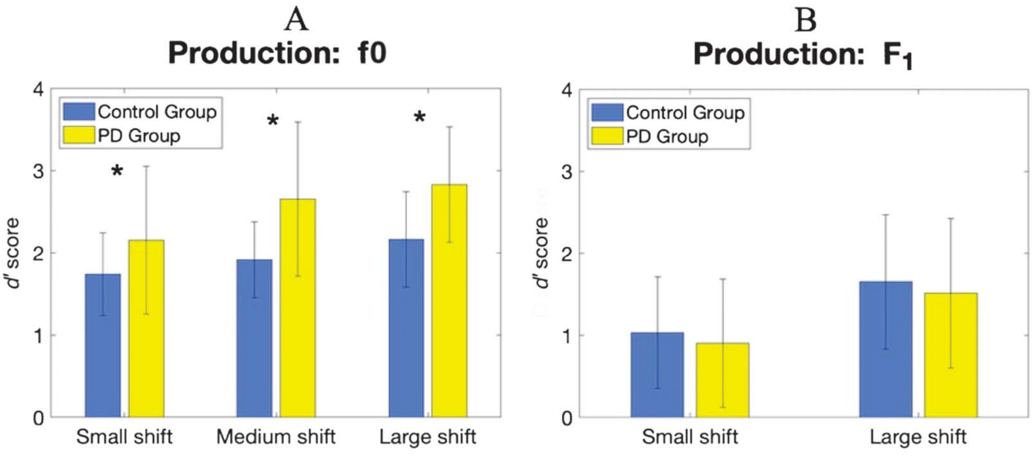


Note. * $p < .01$

the controls showing a greater F_1 change than the PD group), $F(1, 28) = 12.23$, $p < .01$, partial $\eta^2 = .30$, emerged. The two-way interaction was not significant, $F(1, 28) = 1.82$, $p = .19$.

The means and standard deviations (*SD*s) of *d′* scores during the production condition for pitch and F_1 shifts of the two groups are shown in Figure 2. The effects of group (PD and control) and magnitude (small, medium, and large) for pitch were evaluated using a two-way ANOVA. A significant main effect of magnitude, $F(2, 56) = 11.99$, $p < .01$, partial $\eta^2 = .30$, and a significant main effect of group, $F(1, 28) = 6.51$, $p < .01$, partial $\eta^2 = .19$, were found, with no significant two-way interaction, $F(2, 56) = 1.12$, $p = .25$. Further post hoc simple effects analysis showed a significant difference between small and medium, $F(1, 28) = 6.15$, $p < .01$, $r = .42$, and between small and large, $F(1, 28) = 6.03$, $p < .01$, $r = .42$, magnitude conditions, with no significant difference between medium and large conditions, $F(1, 28) = 2.03$, $p = .14$. The effects of group (PD and control) and magnitude (small and large)

Figure 2. (A) The mean of averaged *d′* scores of fundamental frequency (f0) errors (small: 25 cents, medium: 50 cents, large: 100 cents) in those with Parkinson's disease (PD; yellow) and controls (blue) during production (left). (B) Mean of *d′* scores of first formant frequency (F_1) errors (small: 47.5 Hz, large: 135.1 Hz) in those with PD (yellow) and controls (blue) during production (right). Error bars show standard deviation. *$p < .01$.



Note. * $p < .01$

for F_1 modulation were also evaluated using a two-way ANOVA. A significant main effect of magnitude, $F(1, 28) = 30.96$, $p < .01$, partial $\eta^2 = .52$, was noted with no significant main effect of group, $F(1, 28) = 0.16$, $p = .71$, or a two-way interaction, $F(1, 28) = .003$, $p = .94$.

A further analysis focused on the relationship between the degree of compensation (last 100 ms of compensation) and self-monitoring accuracy in the production of f0 and F_1 conditions at each magnitude in both groups. No significant correlations were found for any of the magnitudes for f0 (small magnitude: $r = -.01$, $p = .96$; medium magnitude: $r = -.21$, $p = .46$; large magnitude: $r = -.23$, $p = .41$) or F_1 (small magnitude: $r = .11$, $p = .71$; large magnitude: $r = .19$, $p = .50$).

Experiment 2: Listening

During listening for differences in f0, a significant main effect of magnitude, $F(2, 56) = 98.55$, $p < .01$, partial $\eta^2 = .78$, was found with no significant main effect of group, $F(1, 28) = 0.41$, $p = .52$, or a two-way interaction, $F(2, 56) = 0.52$, $p = .59$. A post hoc analysis focused on the differences among the three magnitudes across both PD and control groups. Significant differences between the small and medium, $F(1, 28) = 52.08$, $p < .01$; small and large, $F(1, 28) = 43.66$, $p < .01$; and medium and large, $F(1, 28) = 59.49$, $p < .01$, magnitude manipulations were found across groups (see Figure 3A). For the detection of F_1 differences, a significant main effect of magnitude, $F(1, 28) = 18.46$, $p < .01$, partial $\eta^2 = .40$, and a significant main effect of group (with controls showing greater sensitivity than the PD group), $F(1, 28) = 7.90$, $p < .01$, partial $\eta^2 = .22$, were found, with no significant two-way interaction, $F(1, 28) = 0.002$, $p = .94$, as shown in Figure 3B.

A further analysis focused on the relationship between the degrees of compensation to f0 or F_1 manipulation and the error detection accuracy in the listening task. No significant correlations were found for any of the magnitudes for f0 (small magnitude: $r = -.16$, $p = .58$; medium magnitude: $r = .23$, $p = .40$; large magnitude: $r = .15$, $p = .58$) and F_1 (small magnitude: $r = .04$, $p = .88$; large magnitude: $r = .08$, $p = .76$).

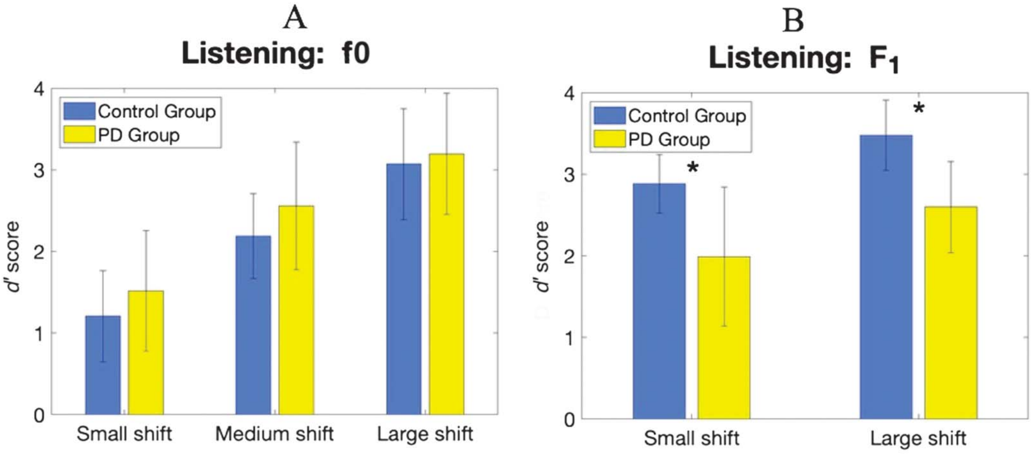
Differences in Detection Between Production and Listening

The effects of task (production vs. listening) and group (control participants and participants with PD) were evaluated with a two-way ANOVA for each manipulation condition (f0 and F_1) separately across perturbation magnitudes (see Figure 4). For the detection of f0 changes, there were no main effect of group, $F(1, 28) = 0.92$, $p = .34$; no significant main effect of task, $F(1, 28) = 0.03$, $p = .85$; and no two-way interaction, $F(1, 28) = 0.45$, $p = .50$. For the detection of F_1 changes, a significant main effect of task, $F(1, 28) = 70.74$, $p < .01$, partial $\eta^2 = .72$, and a significant two-way interaction, $F(1, 28) = 4.70$, $p < .05$, partial $\eta^2 = .14$, was found, but there was no significant main effect of group, $F(1, 28) = 3.49$, $p = .07$. Participants across groups detected speech errors during the listening task significantly more accurately than during the production task ($M \pm SD = 2.73 \pm 0.76$ vs. 1.27 ± 0.61).

Relationship With Clinical Ratings of Severity

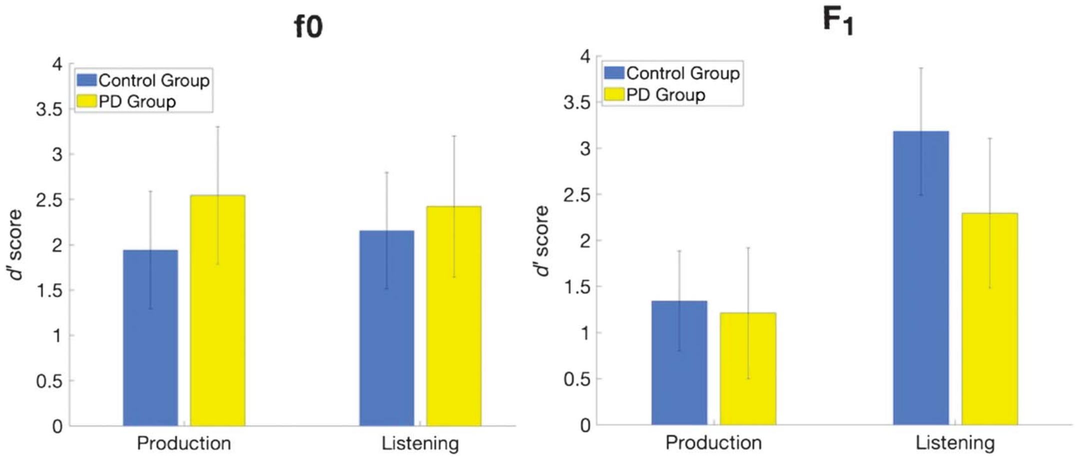
We investigated the relationship between the degree of severity of either the total dysarthria perceptual score or MDS-UPDRS clinical rating score and the ability to detect changes in f0 or F_1 in the PD group (see Table 2) using

Figure 3. (A) The mean of averaged *d′* scores of fundamental frequency (f0) errors (small: 25 cents, medium: 50 cents, large: 100 cents) in those with Parkinson's disease (PD; yellow) and controls (blue) during listening (left). (B) Mean of *d′* scores of first formant frequency (F_1) errors (small: 47.5 Hz, large: 135.1 Hz) in those with PD (yellow) and controls (blue) during listening (right). Error bars show standard deviation. *$p < .01$.



Note. * $p < .01$

Figure 4. The mean of averaged *d′* scores in response to fundamental frequency (f0) errors (left) and in response to first formant frequency (F_1) errors (right) in control participants (blue) and participants with Parkinson's disease (PD; yellow) during production and listening. Error bars show standard deviation.



Pearson correlation analysis. For this analysis, we combined the error detection results across all the magnitudes for each manipulation condition. None of the correlations reached significance using Bonferroni correction for multiple comparisons.

Discussion

Two experiments were conducted to assess the effects of auditory feedback alterations on speech production and speech perception of participants with PD. For the first study, the compensation paradigm was similar to our previous study, and participants with PD responded with a greater compensatory response to medium and large f0 feedback perturbations, while F_1 feedback perturbation resulted in a significant reduction in compensation compared to controls (Mollaei et al., 2016). The current results thus confirm a differential effect of PD on auditory feedback parameters during speech production. For the second study, we examined the ability of individuals with PD to detect their own speech changes immediately following production and under listening conditions, in which judgments were made from samples recorded during the first experiment. Interestingly, different patterns emerged across the two experiments and, importantly, for the two acoustic parameters (f0 and F_1). During self-monitoring while speaking, participants with PD appeared to be more sensitive than control participants to manipulations of f0, but not F_1. However, the results of the listening task revealed that participants with PD were less sensitive than control participants to manipulations of F_1. Possible explanations of these patterns in the context of what is known about speech processing in PD will be outlined in what follows.

Table 2. Correlational analysis between fundamental frequency (f0), first formant frequency (F_1) error detection, and Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) and dysarthria perceptual total scores in Parkinson's disease: Pearson correlation value.

Manipulation	Task	MDS-UPDRS	Total dysarthria score
f0	Production	−.03	−.00
F_1	Production	−.30	−.17
f0	Listening	−.31	−.33
F_1	Listening	−.50	−.56

Comparison of Findings Across Tasks: Pitch

During speech production, participants with PD showed an increased compensatory response to f0 changes (with the exception of the small-magnitude f0 perturbations). This is consistent with prior findings of enhanced responses to f0 perturbations reported in the literature (Chen et al., 2013; Huang et al., 2016; Liu et al., 2012; Mollaei et al., 2016). Participants with PD also demonstrated increased perceptual sensitivity to pitch shifts during production and a trend toward increased sensitivity during listening. This increased sensitivity during production may be related to the observation that, while individuals with PD speak with reduced pitch and loudness modulation, they report their speech to be produced with normal variation in pitch and loudness. However, the response to the small pitch perturbation (25 cents) was reduced in the PD group compared to the control group. It has been reported previously that response to pitch perturbation is related to the shift magnitude, and the auditory system is optimally tuned to compensate for small magnitudes of shift compared to large shifts in healthy control participants (Liu & Larson, 2007). The auditory system is capable of detecting changes as small as 10 cents in magnitude, and the auditory–motor system is capable of compensating for 10 cents of pitch shift (Liu & Larson, 2007). The normal variation in pitch compensation is somewhat opposite of what we observed here in PD, in that, for pitch shifts of 25 cents and below, the percent response magnitude is around 100% (Larson, Burnett, Bauer, Kiran, & Hain, 2001) and, for shifts of above 25 cents, the percent response magnitude is below 50% (Kiran & Larson, 2001). In two previous studies using a pitch compensation paradigm in PD, two different magnitudes of shift (50 and 100 cents) were used (Chen et al., 2013; Mollaei et al., 2016), and they also showed greater sensitivity (gain in response) to the smaller 50-cent shift. The reduced response to the 25-cent shift found in this study suggests that either subtle changes in pitch may not be perceived in PD due to reduced sensitivity to normal variation or their response to the small shifts in pitch is more variable, reducing the overall mean response, as observed in Figure 1A, with high standard deviations for the small shift in the PD group compared to the control group.

The perception of loudness during speech production has been studied more than any other speech parameter in PD and has been shown to be affected by PD (Brajot et al., 2016; Clark et al., 2014; De Keyser et al., 2016; Fox & Ramig, 1997; Ho et al., 2000; Kwan & Whitehill, 2011). Clark et al. (2014) asked participants with PD to produce speech at normal loudness and at two and four times louder and quieter than the normal loudness level. They observed that participants with PD overestimated their own loudness, and when they were asked to make proportional changes in their loudness, they made relatively smaller adjustments in speech intensity despite having adequate capacity to do so. De Keyser et al. (2016) suggested that auditory perceptual deficits may influence speech production in individuals with PD based on their findings from intensity estimation and imitation tasks. They found that individuals with PD had a flatter slope in intensity imitation and a restricted range in intensity estimation compared with control participants. These results suggest abnormal self-monitoring of loudness during speech that may be caused by increased sensitivity at the cortical and/or subcortical level to the transient acoustic parameters of speech such as amplitude and pitch.

During vocalization, vocal fold vibration gives rise to multiple, harmonically related spectral components that create redundancy and enhance the perception of pitch, but not formants. In addition, laryngeal somatosensory information during vocalization (Gozaine & Clark, 2005; Larson, Altman, Liu, & Hain, 2008) adds to the perception of pitch changes compared to the perception of formant changes. Furthermore, the enhanced speech production response to pitch alterations, but not formants, reported here and previously observed (Chen et al., 2013; Huang et al., 2016; Liu et al., 2012; Mollaei et al., 2016) may be partially accounted for by an increased auditory sensitivity to frequencies that fall within the range of f0. The basal ganglia have been associated with gating sensory information by filtering relevant from irrelevant information, and it seems that, in PD, this gating is affected (Haslinger et al., 2001; Liotti et al., 2003; Schneider, Diamond, & Markham, 1987) during speech production and speech perception. Moreover, as initial pitch processing occurs at the level of the brainstem (Aitkin, 1986; Plack, Barker, & Hall, 2014), the enhanced compensatory response to pitch perturbation and increased sensitivity to pitch detection may reflect a release from inhibition due to reduced brainstem dopamine in PD (Nevue, Elde, Perkel, & Portfors, 2016; Nevue, Felix, & Portfors, 2016).

Our results suggest that individuals with PD are more sensitive to pitch-related auditory input during both production and perception for shifts of 50 cents or more. For shifts of 25 cents and below, there may be a reduced sensitivity in detecting and/or correcting for subtle pitch changes during production. The possible deficit associated with somatosensory information in Parkinson's dysarthria (Hammer & Barlow, 2010) and auditory gating deficits may contribute to an increase in sensitivity of the auditory system to f0 by altering the balance between the auditory and somatosensory systems at the level of the brainstem where the neural firing rate encodes pitch (Plack et al., 2014). Further investigation is required to clarify the possible role of brainstem dopamine circuits in pitch and loudness processing in PD.

Comparison of Findings Across Tasks: Formants

The detection accuracy for changes in F_1 was more robust during listening compared to self-monitoring during production for both groups. As has been observed previously from electroencephalographic and magnetoencephalographic recordings, the evoked neural response from self-generated auditory feedback is reduced when compared to listening of the recorded vocalizations from the same participants—the so-called *speech-induced suppression* effect (Heinks-Maldonado, Mathalon, Gray, & Ford, 2005; Houde, Nagarajan, Sekihara, & Merzenich, 2002; Tourville et al., 2008). This suppression effect observed cortically likely reflects a reduced sensitivity to aspects of the auditory input during the production task compared to listening, thereby reducing the overall capacity to identify subtle formant differences. In addition, the acoustic features of the manipulation (involving only F_1 and none of the higher formants) would lead to a less perceptually salient cue compared to f0 shift. These factors may have combined to make the self-monitoring of formant changes more difficult than for f0 changes for listeners in both PD and control groups. Interestingly, in this study at the behavioral level, there was no speech-induced suppression effect observed for f0 detection under the active listening relative to the passive listening condition consistent with a differential modulation of laryngeal pitch compared to the articulatory acoustic parameters.

In contrast to speech production, during listening, the control group demonstrated a better capacity to detect the same subtle formant differences than participants with PD. The difference in detection performance for formant changes during the listening task may reflect a sensory deficit related to more subtle acoustic manipulations in PD. One study that used the same discrimination paradigm as the current study to detect amplitude and frequency of pure tones found reduced detection ability in those with PD compared to healthy controls (Troche et al., 2012). However, there are a number of studies that tested loudness and amplitude perception and did not find any differences in the loudness growth slope (Abur, Lupiani, et al., 2018) or loudness rating (Dromey & Adams, 2000). In addition, Huang et al. (2016) found no differences at the cortical level between individuals with PD and control participants when participants were listening to the frequency-altered feedback of their prerecorded speech. It should be pointed out that these studies used different methodologies to test loudness perception and their inclusion criteria also differed slightly (e.g., in hearing status). For example, Abur, Lupiani, et al. (2018) based their suggestions on a loudness perceptual judgment task for pure tones presented through insert earphones. They included hearing thresholds of 25 dB HL for 1000 Hz and below and 35 dB HL for frequencies above 1000 Hz (Abur, Lupiani, et al., 2018). Dromey and Adams (2000) did not use a hearing screening but tested participants' loudness perception for tones using a magnitude estimation task presented through a loudspeaker at different sound pressure levels. They then correlated participants' hearing thresholds with loudness ratings and found no significant correlation. Huang et al. used a passive listening task that included pitch-shifted recordings of participants' speech presented through insert earphones, and they included hearing thresholds of 40 dB HL or less for 500, 1000, 2000, and 4000 Hz. Abur, Lupiani, et al. and Dromey and Adams tested individuals with PD on medication; however, in our study, individuals with PD were off medication for 12 hr. The effect of medication on speech perception and production in PD certainly requires further investigation. The current findings indicate that individuals with PD have speech monitoring deficits at least for the articulatory parameter of F_1. The findings also point to the heterogeneous effects of the disorder on error monitoring for pitch versus F_1.

Relationship of Compensation Responses and Severity to Detection Accuracy

No correlation was found between detection accuracy during speech self-monitoring or listening and compensation responses in both f0 and F_1, consistent with recent findings of unimpaired verbal monitoring in PD, at least at the single word level (Gauvin et al., 2017; however, see also McNamara et al., 1992). However, the lack of correlation between speech production and perception system may be due to the small sample size in the current study. Additionally, we did not find any relationship between detection accuracy across all perturbation magnitudes in f0 or F_1 and disease severity in MDS-UPDRS or perceptual dysarthria scores using total speech subsystems. These nonsignificant results are consistent with the findings from our prior study in the relationship between f0 or F_1 compensation responses and MDS-UPDRS or perceptual dysarthria scores (Mollaei et al., 2016).

Limitations and Future Directions

The error detection of f0 in the listening task showed a trend toward better performance in PD, but the trend was not statistically significant, most likely due to the small sample size. In addition, the heterogeneous nature of the disorder and the state of the participants with PD at the time of testing limit the ability to fully interpret differences due to disease severity. Individuals with PD showed a wide range of MDS-UPDRS motor scores (3–48). It would be useful in future studies to increase the sample size to obtain a better distribution of severity to assess the effects of disease severity on perceptual processing. Although participants were tested off medication for 12 hr, based on disease severity and the L-dopa dosage, it is difficult to determine the degree of "on" or "off" state of PD symptoms, as it does not have a linear relationship with medication intake (Fern-Pollak, Whone, Brooks, & Mehta, 2004). As such, evaluating symptom severity immediately prior to the onset of testing may provide a better indication of the state of the disease at the time of testing. In addition, the MDS-UPDRS was assessed by the first author, who received in-house training but did not hold official certification for the examination. This may have affected its reliability, although a second trained rater provided comparable scores.

Conclusion

The current results and previous findings support the hypothesis that individuals with PD demonstrate differential perceptual sensitivity to speech acoustic parameters. Overall, the results of the present investigation provide insight into the production and perceptual deficits in PD. The increased detection accuracy for pitch while producing speech and reduced detection accuracy for F_1 during listening further highlight the differential effects of the disease on speech perception and point to speech error monitoring deficits in PD. The lack of correlation between compensation responses and error monitoring ability in PD makes it difficult to relate the speech production deficits to perceptual disorders; however, including a larger sample size in future studies may help pinpoint the relationship of speech perception and speech production deficits in PD. In addition, future investigation should focus on the exact neurobiological underpinnings of these auditory perceptual deficits, specifically increased sensitivity to pitch changes in PD.

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