ASHA American Speech-Language-Hearing Association

JSLHR

Research Article

Kinematic and Acoustic Responses to Predictable and Unexpected Auditory Feedback Perturbations in Speakers With and Without Parkinson's Disease

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ARTICLE INFO

Article History:
Received October 3, 2024
Revision received April 16, 2025
Accepted December 9, 2025

Editor-in-Chief: Rita R. Patel
Editor: Kelly Richardson

https://doi.org/10.1044/2025_JSLHR-24-00697

ABSTRACT

Purpose: Individuals with Parkinson's disease (IwPD) frequently suffer from speech articulation impairments that result in reduced intelligibility. While some studies have previously investigated auditory feedback and feedforward mechanisms as potential explanations behind these impairments, they have done so using only acoustic measures, which may not be sensitive enough to capture small changes. The current study assessed the sensorimotor control of speech articulation in IwPD and control speakers (CS) by measuring both acoustic and kinematic responses to either predictable or unexpected errors in auditory feedback while participants were speaking.
Method: We employed two formant perturbation tasks: a predictable (upward) vowel perturbation task and an unexpected (upward and downward) vowel perturbation task. A total of 33 IwPD on levodopa and 25 CS performed the tasks, while their speech was recorded acoustically with a microphone and kinematically with sensors placed on the tongue and the jaw. We analyzed acoustic (first and second formant frequencies) and kinematic (jaw and tongue height and backness) correlates of vowel perturbation task responses using generalized additive modeling.
Results: In the predictable vowel perturbation task, IwPD and CS did not differ in their responses in kinematic or acoustic measures. In the unexpected vowel perturbation task, we found differences between the two groups in both acoustics and kinematics for the downward perturbation, but not for the upward perturbation. For the unexpected downward perturbation, IwPD responded more slowly and to a lesser degree than did CS when vowel trajectories were modeled using the second formant and kinematic tongue body height.
Conclusions: IwPD showed a reduced ability to correct unexpected errors in auditory feedback both acoustically and kinematically but retained the ability to update their speech sensorimotor maps based on predictable errors in auditory feedback. This study expands on existing assessments of language- and speech-related impairments in Parkinson's disease by highlighting important potential differences in sensorimotor control of speech articulation.

Speech impairments are common in Parkinson's disease (PD), occurring in 70%–90% of individuals throughout the course of the disease (Hartelius & Svensson, 1994; Ho et al., 1998; Schalling et al., 2018). While all speech subsystems, including

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respiration, phonation, and articulation, can be affected in individuals with PD (IwPD; Broadfoot et al., 2019; Pinto et al., 2004), our focus is on impairments in the articulatory subsystem. These tend to occur later in the disease when the motor symptoms worsen (e.g., Skodda et al., 2012) and are closely tied to perceived speech impairment (Convey et al., 2024; Johansson et al., 2023; Kim & Choi, 2017; McRae et al., 2002; Skodda et al., 2012) and reduced intelligibility (Anand & Stepp, 2015; Stipancic & Tjaden, 2022; Thompson & Kim, 2024), which can severely impact IwPD's ability to communicate effectively (Miller, 2017). The origin of speech impairments in PD in general (Moreau & Pinto, 2019), and articulation impairments in particular, remains unknown, and multiple levels of impaired underlying mechanisms could be at fault, including impaired sensory (auditory or somatosensory) processing, motor learning, and motor execution. The current study focuses on investigating these in the context of potentially diminished integration of auditory feedback, as it has previously been proposed that speech impairments in PD are a result of speech motor representations that deteriorate due to consistently misprocessed auditory information (Arnold et al., 2014; Moreau & Pinto, 2019).

Fluent articulation necessitates planning speech in advance ("feedforward control"), smoothly executing the planned motor actions ("motor execution"), and integrating the relevant incoming sensory information ("feedback control"). As explained by one influential neurocomputational model of speech motor control, the Directions Into Velocities of Articulators (DIVA) model (Tourville & Guenther, 2011), feedforward control ensures that we can plan the timing and gain of the articulator movements based on existing speech sound maps, as well as initiate these movements in a timely and coordinated manner. At the same time, feedback control ensures that we process all relevant incoming auditory and somatosensory information.

One of the characteristics of impaired speech articulation in PD is diminished articulatory movements, which have been reported kinematically and acoustically, indicating issues with motor execution and potential underlying impairment in feedforward control. For example, lingual movements can be smaller, with decreased movement velocities and longer movement duration for IwPD compared to control speakers (CS; Kuruvilla-Dugdale et al., 2020; Thies et al., 2023). Similarly, jaw and lip movements and velocity can be significantly reduced in IwPD (Forrest et al., 1989; Kearney et al., 2017; Kuruvilla-Dugdale et al., 2020; Walsh & Smith, 2012). Acoustically, the vowel space has generally been found to be smaller in IwPD compared to CS (Kuo & Berry, 2023; Skodda et al., 2011; Whitfield & Goberman, 2014), although some studies have found no differences (e.g., Houle et al., 2024).

These articulation issues are possibly exacerbated by some known issues with the somatosensory feedback for the articulators. For example, IwPD have shown impaired proprioception of the jaw and a decreased ability to localize sensory input on the tongue (Schneider et al., 1986), as well as reduced acuity of the tongue tip (Chen & Watson, 2017), compared to controls. It is furthermore unclear how bradykinesia (i.e., slowness of movement) and rigidity, as two of the leading PD symptoms, influence articulation. While one study by Caligiuri (1987) found no significant direct relationship between labial rigidity and impaired orofacial movement during a fast syllable repetition task, other studies have found more severe speech impairments in IwPD who suffer from bradykinesia, rigidity, and postural and gait difficulties (e.g., Tykalova et al., 2022). This, then, would indicate rigidity and bradykinesia as potential influencing factors in the previously reported decreased movement velocities of the articulators.

IwPD are furthermore impacted by sensory impairments at the auditory level. At a domain-general level, IwPD display higher instances of hearing loss compared to age-matched peers (e.g., Shetty et al., 2019), as well as aberrant auditory processing in the auditory cortex and associated areas. For example, prior studies using electrophysiological measures have shown both a reduced ability to detect small auditory changes and impairments in learning novel auditory information (see a review in Jafari et al., 2020). For speech, among others, IwPD show some impairments in the perception of loudness (Clark et al., 2014; Ho et al., 2000) and prosody (e.g., Lima et al., 2013). These impairments (see also a review by De Groote et al., 2020) do not seem to extend to spectral and temporal features related to speech articulation, however. For example, IwPD display similar perceptual acuity to formants as CS (Abur et al., 2021; Ravizza, 2003).

It therefore remains unclear how feedforward control, motor execution, and feedback control interact in the case of articulation impairments in PD. This, however, can be directly investigated. Integration of sensory feedback for speech motor control is often assessed using feedback perturbation paradigms that induce errors in either auditory or somatosensory feedback (Guenther, 2016; Houde & Jordan, 1998). There are two main types of auditory feedback perturbation paradigms: The perturbation can be applied either in a gradual and predictable manner, assessing the speaker's ability to integrate auditory feedback for motor learning and adapt feedforward commands ("adaptive responses"), or in a sudden and unexpected manner, assessing the speaker's ability to immediately detect and correct errors ("reflexive responses"). Both types of auditory feedback perturbation paradigms can be applied to assess feedback and feedforward control of articulation (by shifting vowel formants) or voice (by shifting fundamental frequency).

Most auditory feedback perturbation studies with IwPD have targeted only the laryngeal subsystem by perturbing the fundamental frequency. For a detailed discussion of sensorimotor impairments at the laryngeal level, see Abur et al. (2021). Fewer studies have assessed articulatory sensorimotor control in IwPD by perturbing vowel formants (the first and second formants [F_1 and F_2]). These studies have shown that IwPD off medication show reduced reflexive vowel formant responses compared to CS (Mollaei et al., 2016; 15 IwPD/15 CS), suggesting an impaired ability to correct errors in auditory feedback and integrate incoming auditory information. IwPD off medication likewise show reduced adaptive vowel formant responses (Mollaei et al., 2013: nine IwPD/nine CS, but not sex balanced), indicating motor learning impairments. Conversely, IwPD on medication have shown reflexive and adaptive responses similar to those of CS (Abur et al., 2021; 28 IwPD/28 CS), suggesting that levodopa (the drug most commonly prescribed for IwPD' motor symptoms; Zach et al., 2020) has a largely ameliorating effect on the integration of auditory feedback for vowel formants and should thus also help with articulation impairments.

As IwPD take levodopa to be able to function in their daily lives, examining IwPD on medication is crucial for ecological validity and has important implications for designing better speech therapies (Thies et al., 2021; Weerathunge et al., 2022). Importantly, however, it is not entirely clear which aspects of articulatory motor control are impaired in IwPD on medication and whether acoustic measures are sensitive enough to capture the potential differences between IwPD and CS. For example, current results from the single prior published formant perturbation study of IwPD on medication (Abur et al., 2021) seemingly provide evidence for preserved integration of auditory feedback for articulation in IwPD on medication. However, this finding does not entirely align with findings from acoustic and kinematic studies of articulation in PD on medication. For example, articulation, when measured acoustically, does not seem to be impacted by levodopa (Houle et al., 2024; Rusz et al., 2016; Skodda et al., 2010; Tykalova et al., 2022), even when other (motor) function improves (Tykalova et al., 2022: 60 IwPD/30 CS). Conversely, the tongue body is more flexible for vocalic movements after levodopa intake, even if this is not detectable at the acoustic level (Thies et al., 2021: 16 IwPD). In line with this, IwPD have been shown to compensate for an impairment in one articulator by an increased use of another (Mefferd & Dietrich, 2019; 17 IwPD/17 CS).

Thus, there is a discrepancy between results from acoustic and kinematic studies of articulation and studies assessing the integration of auditory feedback for formants. The former clearly show articulatory impairments of IwPD, while the latter show similar functioning in IwPD and CS. However, as formant perturbation studies so far only captured acoustically measured responses but not the underlying movements executed in order to obtain these responses, it remains unclear whether IwPD perform similarly to CS or take advantage of compensatory behaviors. In other words, to fully investigate auditory feedback integration for formants, it is necessary to go beyond only acoustic information.

Collecting kinematic data can shed new light on this, as it allows us to look at changes in the speech movements themselves and in the associated vowel acoustics. In the case of vowel formants, it is generally assumed that tongue height is inversely related to F_1, while F_2 is related to changes in both tongue height and backness (Lee et al., 2016; Thompson & Kim, 2019). Jaw height, conversely, determines the degree of vowel openness (Lindblom & Sundberg, 1971), which is associated with F_1. However, this is also dependent on target vowels, as changes in tongue and/or jaw posture may have greater acoustic consequences within some regions of the vocal tract compared to others (i.e., quantal effects; Gick & Moisik, 2015; Stevens, 1989). For example, during the production of /a/, the jaw can be lowered to various degrees without a noticeable change in F_1 and F_2 (Perkell & Cohen, 1989).

The relationship between formants and jaw/tongue positions is therefore imperfect, as each speech sound can be produced with multiple configurations of the vocal tract and still result in the same acoustic output (i.e., motor equivalence; Perrier & Fuchs, 2015; Stevens, 1989). There is a trading relationship between kinematic strategies that can change acoustic output: As exemplified above, both tongue and jaw height changes can result in changes to F_1, but dependent on the vowel in question, differences in kinematics may not necessarily be audible or measurable in the acoustics (as also shown in Thies et al., 2021). This was also demonstrated in the only prior study investigating kinematic responses to an auditory vowel formant perturbation (Max et al., 2003: eight typical young speakers), in which speakers showed motor-equivalent adaptations in overall gestures but not any specific articulator trajectory. In the case of IwPD, impaired articulation without impaired auditory feedback integration could at least partly be explained through quantal effects and kinematic differences in magnitude that are not apparent from the acoustics. To determine where articulation impairments in IwPD stem from, kinematic measures of speech motor control across individuals are therefore necessary as they allow us to assess whether IwPD respond to auditory perturbations in ways that are not acoustically measurable and whether articulatory strategies differ between IwPD and CS, which would be in line with some kinematic studies that have shown the compensatory behavior of the tongue in IwPD (e.g., Kearney et al., 2017; Mefferd & Dietrich, 2019).

The goal of the current study was therefore to assess the sensorimotor control of articulation in IwPD by probing both the auditory feedforward and feedback systems while simultaneously accounting for changes on both the acoustic and kinematic levels. Specifically, by assessing adaptive responses to a predictable auditory feedback perturbation, we can assess how well IwPD and CS integrate auditory feedback for motor learning. In order to successfully adapt their speech, a speaker needs to detect the perturbation (feedback control), update their internal maps (feedforward control), and execute a new plan (motor execution). Conversely, by assessing reflexive responses to an unexpected perturbation, we can determine whether the immediate integration of auditory feedback is affected and whether the compensation is existent but potentially slower due to difficulties in motor execution. Here, the speaker does not need to update their internal maps; however, they do need to quickly integrate auditory feedback and execute corrective responses at a much faster rate (i.e., within the same vowel as opposed to across multiple repetitions of vowels).

Based on prior studies by Abur et al. (2021), we expect no differences between IwPD and CS in the acoustic output. There are no prior studies directly investigating the kinematics of responses to auditory feedback perturbation of formants. However, based on prior kinematic studies showing smaller speech movements in IwPD (e.g., Raines & Mefferd, 2024; Walsh & Smith, 2012) and IwPD taking advantage of compensatory movements (e.g., Kearney et al., 2017; Mefferd & Dietrich, 2019), we potentially do expect some impairments in IwPD's movement execution to be kinematically detectable compared to CS. These could show as compensatory movements in both tasks (i.e., IwPD use different kinematic strategies to achieve the same acoustic result as that of controls) but would more easily be detectable in the unexpected perturbation task, which relies on quickly implemented changes in speech movements.

Materials and Method

This study was approved by the Medical Ethics Review Board of the University Medical Centre Groningen (NL72589.042.21) prior to participant recruitment taking place.

Participants

A total of 33 IwPD participated in the study, including 18 men ($M_{\text{age}} = 71.6 \pm 5.6$ years) and 15 women ($M_{\text{age}} = 66.6 \pm 8.6$ years). In addition, 25 CS participated, including 14 men ($M_{\text{age}} = 67.9 \pm 8.4$ years) and 11 women ($M_{\text{age}} = 69.2 \pm 5.4$ years). All participants were native speakers of Dutch, underwent a cognitive screening using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), and were included only if they were still capable of giving consent (i.e., reaching the required score of 22/30 points on the MoCA; Karlawish et al., 2013). The participants additionally completed a hearing screening at cutoffs for older adults (25 dB at 250, 500, and 1000 Hz; 40 dB at 2000 and 4000 Hz; Schow, 1991). Per classification of the Global Burden Disease Expert Group on Hearing Loss (Olusanya et al., 2019), which uses the average decibel hearing level at 500, 1000, 2000, and 4000 Hz in the better ear, 37 participants (19 IwPD, 18 CS) had none or mild hearing loss (hearing level up to 34.9 dB), 19 participants (13 IwPD, six CS) suffered from moderate hearing loss (hearing level up to 49.9 dB), and two participants (one IwPD, one CS) suffered from moderately severe hearing loss (hearing level up to 64.9 dB). Due to our testing protocol, which included cutoffs for older adults only, we were not able to distinguish between individuals with no hearing loss and those with mild hearing loss.

IwPD additionally completed Parts I–III of the Movement Disorder Society–sponsored revision of the Parkinson's Disease Rating Scale (MDS-UPDRS; Goetz et al., 2008). Mean MDS-UPDRS Part III score was 38 points (SD = 17.2 points, range: 18–71 points) for male IwPD and 36 points (SD = 21.2 points, range: 11–83 points) for female IwPD. All IwPD were tested while on levodopa. Participant demographics for IwPD and CS are reported in Tables 1 and 2, respectively.

Speech Severity Ratings and Self-Assessment of Speech Problems

In addition to the demographic information collected above, we collected speech severity ratings for both IwPD and CS. We additionally asked IwPD questions related to potential speech impairments. For the speech severity ratings, 41 inexperienced listeners (16 men, 25 women) without any self-reported speech, language, or hearing impairments were recruited to rate spontaneous speech recordings of the speakers on a visual analog scale (Abur et al., 2019). They were asked to rate speech severity (Sussman & Tjaden, 2012) on a scale from 1 to 100, where 1 indicated *severely impaired speech* and 100 indicated *completely unimpaired ("typical") speech*. They were given instructions to rate the overall speech severity by paying attention to voice quality, resonance, articulatory precision, and speech rhythm (as in Sussman & Tjaden, 2012, p. 1213). There were two lists of stimuli, whereby List 1 contained 32 samples to rate, whereas List 2 contained 30 samples to rate.[1] Each spontaneous speech sample was rated by either 20 listeners (List 1) or 21 listeners (List 2).

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[1] The discrepancy between the number of speakers in the current study (N = 58) and the number of samples in the listening experiment (N = 62) is due to the fact that four participants included in the bigger project did not complete the study reported here.

Table 1. Demographics of individuals with Parkinson's disease (PD), including age (in years), sex, Movement Disorder Society–sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS UPDRS) Part III motor scores, motor phenotype, hearing severity assessment, speech severity assessment (higher numbers indicate speech that is perceived as more typical), and articulation and phonation assessments (higher numbers indicate more self-perceived speech impairment in that category).

Participant	Age	Sex	MDS UPDRS Part III	Phenotype	Hearing impairment	Severity assessment	Articulation /6	Phonation /6
PD01	72	M	34	TD	Moderate	38	2	2
PD02	72	M	31	TD	Moderate	66	2	4
PD03	62	F	21	TD	Moderate	59	0	0
PD05	69	F	32	PIGD	None to mild	51	2	1
PD06	80	M	32	PIGD	Moderate	57	4	2
PD07	63	F	16	TD	None to mild	65	2	0
PD08	63	F	18	TD	None to mild	82	1	2
PD09	78	M	29	TD	Moderate	68	1	1
PD10	72	M	48	PIGD	None to mild	58	3	2
PD11	67	M	25	Ind	Moderate	69	0	0
PD12	79	M	58	TD	Moderate	62	1	2
PD13	82	F	41	TD	Moderate	53	0	0
PD14	75	M	61	TD	None to mild	60	5	3
PD15	70	M	64	PIGD	None to mild	21	4	4
PD16	69	M	35	TD	Moderate	39	2	0
PD19	54	F	14	TD	None to mild	84	1	1
PD20	71	F	47	PIGD	Moderate	61	2	2
PD21	60	F	11	TD	None to mild	77	0	0
PD22	66	F	83	Ind	None to mild	32	4	3
PD23	66	M	18	TD	None to mild	46	2	3
PD24	76	M	27	PIGD	None to mild	51	0	0
PD25	72	F	26	TD	Moderate	77	2	0
PD26	70	M	21	TD	None to mild	30	3	4
PD29	77	M	71	PIGD	Moderate	12	5	5
PD30	77	M	58	TD	Moderate	44	2	2
PD31	73	F	29	TD	None to mild	57	0	0
PD32	59	M	20	TD	None to mild	49	3	4
PD33	54	F	29	TD	None to mild	74	2	2
PD35	67	M	30	TD	None to mild	69	0	2
PD37	78	F	60	Ind	Moderately severe	27	4	6
PD38	74	F	69	PIGD	None to mild	39	4	5
PD39	57	F	41	TD	None to mild	48	4	4
PD40	65	M	21	PIGD	None to mild	60	3	3

Note. M = male; TD = tremor dominant; F = female; PIGD = postural instability/gait difficulty; Ind = indeterminate.

Intrarater reliability was calculated using two-way mixed-effects interclass correlation coefficients (ICCs) on 10% of repeated stimuli. A total of 21 listeners showed good or excellent reliability (ICC > .75), 13 listeners showed moderate reliability (.50 < ICC > .75), and seven listeners showed poor to very poor reliability (ICC < .50). These seven listeners were excluded when calculating average speaker severity assessment scores. Severity assessments are provided in Tables 1 and 2.

For self-assessments, IwPD completed a questionnaire with 23 statements targeting different potential speech impairments that can occur on the articulatory, laryngeal, suprasegmental, and linguistic levels of speech (see the Appendix). Summed participant responses are in Table 1: Each affirmative answer counted as 1 point, leading to a total of 6 possible points for laryngeal impairment and 6 possible points for articulatory impairment. Higher numbers represent higher levels of self-reported speech problems (i.e., more impaired speech).

Auditory Formant Perturbation Tasks

Participants completed a predictable auditory formant perturbation task to elicit adaptive responses, as well as an unexpected auditory formant perturbation task to

Table 2. Demographics of control speakers (CS), including age (in years), sex, hearing severity assessment, and speech severity assessment (higher numbers indicate speech that is perceived as more typical).

Participant	Age	Sex	Hearing impairment	Severity assessment
CS02	71	F	Moderate	76
CS03	70	F	Moderately severe	93
CS06	64	M	None to mild	67
CS07	74	F	None to mild	68
CS08	71	M	Moderate	80
CS09	78	M	None to mild	58
CS10	66	F	None to mild	69
CS11	80	F	Moderate	68
CS12	67	M	None to mild	85
CS13	68	F	None to mild	81
CS14	68	M	Moderate	75
CS15	77	M	None to mild	62
CS16	66	M	None to mild	86
CS18	55	M	None to mild	82
CS19	70	M	None to mild	59
CS20	63	M	None to mild	78
CS21	72	F	None to mild	73
CS24	62	F	None to mild	80
CS25	56	M	None to mild	84
CS27	68	F	None to mild	57
CS29	81	M	None to mild	55
CS30	78	M	Moderate	48
CS31	58	M	None to mild	74
CS32	71	F	Moderate	74
CS33	61	F	None to mild	82

Note. F = female; M = male.

elicit reflexive responses. During the predictable perturbation task, the participants completed 120 trials with six target words containing the open-mid front unrounded vowel /ɛ/ (e.g., *pet*, /pɛt/, meaning "a cap"). Besides *pet* (/pɛt/, "a cap"), the other words in the adaptive formant perturbation experiment included *bed* (/bɛt/, "bed"), *zet* (/zɛt/, "move"), *vet* (/fɛt/, "fat"), *wet* (/vɛt/, "law"), and *net* (/nɛt/, "mesh"). For the reflexive formant perturbation experiment, we did not include the words *vet* and *net* but instead added *bek* (/bɛk/, "beak") and *dek* (/dɛk/, "deck"). For all words, the downward and upward shifts resulted in a semantically meaningful word. For both tasks, we chose to perturb both the first and second formants. This better represents real speech, as perturbing both formants is more likely to be perceived as a categorical error and therefore more likely to induce larger response magnitudes (Daliri et al., 2020).

Following a common setup for predictable perturbation tasks (Cai et al., 2010; Parrell et al., 2017; Stepp et al., 2017), participants produced the target words while receiving unperturbed auditory feedback via earphones for the first 24 trials (baseline phase), followed by 24 trials during which the perturbation was gradually ramped upward[2] in vowel formant space (ramp phase) until reaching the maximal 20% decrease in F_1 and 15% increase in F_2.

During the maximum perturbation, which lasted for 48 trials (hold phase), the participants heard themselves say a vowel that sounded more like /ɪ/ (e.g., *pit*, /pɪt/, meaning "a seed" or "pit"). For the final 24 trials, the perturbation was removed (after-effect phase). Participants were encouraged to produce the words with emphasis, to ensure each vowel was at least 100 ms long. Each trial was followed by an interstimulus interval of around 5 s. Figure 1 visualizes the predictable formant perturbation paradigm. The task took around 10 min to complete and was followed by a brief break and the unexpected perturbation task.

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[2] Note that, in our study, we refer to the "upward" perturbation condition when the perturbation shifts the vowel upward in the vowel space (F_1 decrease and F_2 increase shift /ɛ/ to /ɪ/), and we refer to a "downward" perturbation condition when the perturbation shifts the vowel downward in the vowel space (F_1 increase and F_2 decrease shift /ɛ/ to /ɑ/). This is in contrast with some other studies that do not perturb both formants and refer to the upward condition when F_1 is increased.

During the unexpected perturbation task, the participants produced 120 repetitions of six target words in three conditions: upward perturbed, downward perturbed, and nonperturbed control trials. We chose to perturb in both directions (see, e.g., Parrell et al., 2017) to reduce the potential learning effect from the gradual perturbation task and prevent additional learning. In the upward perturbed condition, F_1 was decreased by 20% and F_2 increased by 15%, resulting in a perceived change from /ɛ/ to /ɪ/ (as in the predictable perturbation task). In the downward perturbed condition, F_1 was increased by 20% and F_2 decreased by 15%, resulting in a perceived change from /ɛ/ to /ɑ/ (i.e., from *pet*, /pɛt/, meaning "a cap," to *pat,* /pɑt/, meaning "tab" or "toad"). In the control (nonperturbed) condition, the participants' production remained unchanged. The conditions were randomly distributed such that each downward or upward perturbed trial had to be preceded by at least one nonperturbed trial. This resulted in 90 nonperturbed trials, 15 upward perturbed trials, and 15 downward perturbed trials. The formant perturbation occurred at vocalization onset. Participants were encouraged to produce vowel vocalizations of at least 500 ms to ensure that the reflexive response, occurring at 100–200 ms after the perturbation onset (Daliri et al., 2020; Tourville et al., 2008), could be captured. This task also took around 10 min to complete. Figure 2 illustrates the unexpected perturbation task paradigm.

For both tasks, participants wore the Shure MX153 headset microphone and heard their voice through Sennheiser IE 100 PRO earphones, amplified by +5 dB relative to the microphone to overcome bone-conducted auditory feedback (Weerathunge et al., 2020). Auditory formant perturbation was done with Audapter (Version 2.1; Cai et al., 2008, 2010), in MATLAB 2020a (The MathWorks, Inc.). Kinematic data were simultaneously collected using the Northern Digital Inc. VOX-EMA electromagnetic articulograph (Rebernik, Jacobi, Tiede, & Wieling, 2021). Electromagnetic articulography (EMA) is a technique whereby sensors are placed on the articulators to track movements in real time in a coordinate system (Perkell et al., 1992). We used five movement sensors on the tongue tip, placed 1 cm from the apex; the tongue body, placed at the /k/ constriction; chin (to track jaw movements; hereinafter JAW), and upper and lower lips, following the procedures reported in Rebernik, Jacobi, Jonkers, et al. (2021). Attached sensors are depicted in Figure 3. All experimental tasks were conducted in a sound-dampened booth.

Data Preprocessing

For the acoustic data, three investigators manually annotated all trials in Praat (Version 6.3.15; Boersma & Weenink, 2019), and extracted formants using an automated script (Carignan, 2022). Manual vowel segmentations were checked and verified by the first author to ensure intrarater reliability. The kinematic data from EMA sensors were first corrected by frame for head movement by subtracting positional information from three reference sensors (left/right mastoid processes and the upper incisors) and rotating to the occlusal plane with the help of a biteplane recording collected at the beginning of each session. This ensured that all

Figure 1. Visualization of the predictable formant perturbation paradigm.

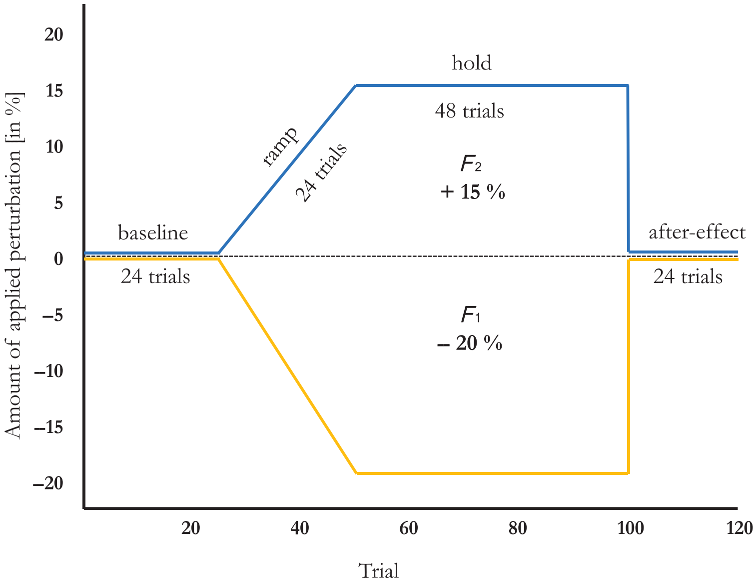
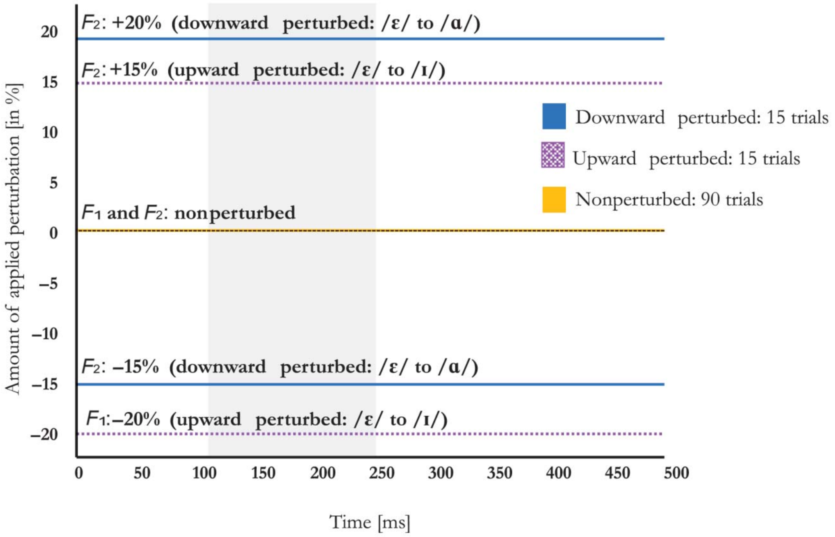


Figure 2. Visualization of the unexpected formant perturbation paradigm.

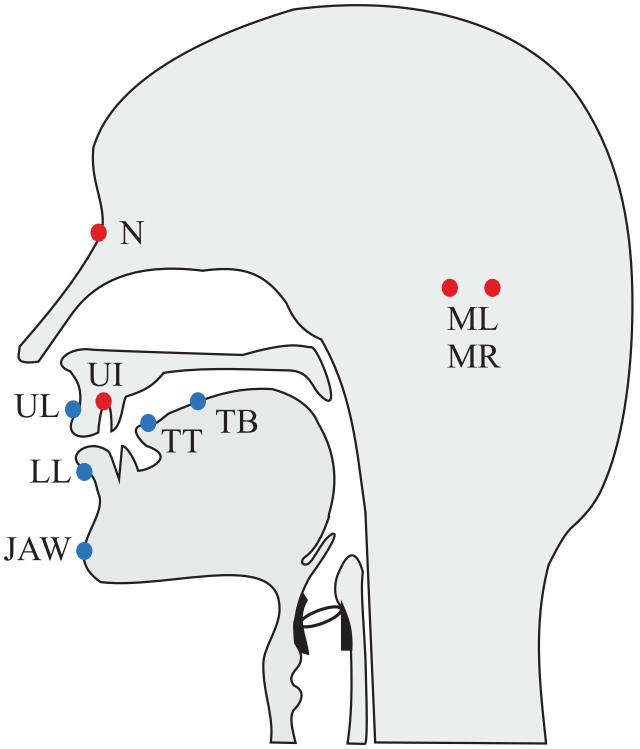


sensor positions across speakers were located in a common coordinate system. The kinematic data were subsequently coupled with the acoustic data using an in-house R script, matching the extracted time of the sensor coordinates to the manually annotated vowel. All sensor coordinates were thus extracted based on acoustically set landmarks and precisely matched the timing of the extracted vowel formants.

To measure participants' adaptation during the predictable perturbation task, we calculated the average value per trial between 20% and 60% of the vowel up to the first 200 ms of vowel duration. This ensured that the time window of 40–120 ms of the vowel (following Abur et al., 2021, and capturing the feedforward portion of the response) was measured for vowels longer than 200 ms, but a stable midpoint was still captured for vowels shorter than 200 ms. For acoustic data, the average value across 20%–60% of the vowel was extracted in hertz. For kinematic data, the average value was extracted in millimeters per sensor trajectory for the same time frame.

To measure participants' reflexive responses during the unexpected perturbation task, we kept the vowel trajectory of the first 400 ms of the vowel in 5-ms increments for both acoustic data (in hertz) and kinematic data (in millimeters). We chose to analyze the entire response in order to capture both the early involuntary response capturing feedback control (120–240 ms; Abur et al., 2021) and the later voluntary response (300–400 ms; Hain et al., 2000; Mollaei et al., 2016; Tourville et al., 2008). Reflexive trials shorter than 400 ms were excluded. For both tasks, we standardized the data by *z* scoring all data points relative to the mean and standard deviation based on nonperturbed (control) trials.

Figure 3. Placement of electromagnetic articulography sensors: The blue dots represent movement sensors (TT = tongue tip; TB = tongue body; LL = lower lip; UL = upper lip; JAW = jaw), whereas the red dots represent the reference sensors (N = nasion; ML/MR = left and right mastoid processes; UI = upper incisor).



Participant Subgrouping and Exclusion

Not all participants completed both speech perturbation tasks, and not all sensors could be placed for all participants. The adaptive task was completed by all participants, which included 33 IwPD (18 men, 15 women) and 25 CS (14 men, 11 women). For the reflexive task, a subset of participants had to be excluded, either because they could not complete the task due to fatigue ($n = 6$) or because they did not produce vowels that were long enough for an adequate analysis ($n = 7$). Consequently, 23 IwPD (12 men, 11 women) and 22 CS (10 men, 11 women) were included.

The EMA sensor for the tongue body did not always properly adhere, so only a subset of the participants had complete data sets for both tasks. For the adaptive task, this included 15 IwPD (nine men, six women) and 14 CS (nine men, five women), while for the reflexive task, this included 12 IwPD (seven men, five women) and 11 CS (six men, five women). The results are therefore reported in two parts: one for the whole group of participants and one for the subgroup for whom all sensors could be placed.

Statistical Analysis

Generalized additive mixed modeling (GAMM; Hastie & Tibshirani, 1990; Wood, 2017), a nonlinear mixed-effects regression technique, was used to model reflexive and adaptive responses in the acoustic and kinematic domains. Unlike repeated-measures or two-way analyses of variance, both of which are frequently used for the analysis of auditory feedback perturbation responses, GAMMs allow us to model potentially nonlinear participant responses using smooths.

Due to the missing sensor data, we ran two models for both the predictable and unexpected perturbation tasks: one model with all participants, including only the two acoustic measures and jaw height, and one model with the subset of participants who had all acoustic and kinematic measures. The reported p values have been corrected for multiple comparisons with false discovery rate (fdr; Benjamini & Hochberg, 1995) using the *p.adjust* function in R. The α level was set at .05.

The hypothesis-testing model for the predictable perturbation task included a nonlinear effect over trial, capturing the changes in the acoustic (F_1 and F_2) and kinematic (tongue tip backness and height [TT_x, TT_y], tongue body backness and height [TB_x, TB_y], jaw backness and height as measured through the sensor on the chin [JAW_x, JAW_y]) measures, with a binary difference smooth for group (per measure), assessing whether the acoustic and kinematic change pattern differed between IwPD and CS. This effectively tests an interaction effect between trial and group, per measure. The hypothesis-testing model for the unexpected perturbation task included a nonlinear effect over the 400-ms vowel trajectory by group, with a binary difference smooth for group and condition (per measure), assessing whether trajectories between conditions (nonperturbed, upward perturbed, downward perturbed) differed between IwPD and CS.

As the residuals of our model were not normally distributed and showed heavy tails, we fitted the final models using the scaled-t distribution. For the random-effects structure, we used the maximal random-effects structure supported by the data to yield the most conservative estimates (van Rij et al., 2019). That included accounting for variation in participants and target words. Autocorrelation in the unexpected perturbation data was accounted for by setting the rho value based on the autocorrelation value of the initial model. All GAMM analyses were conducted in R (Version 4.4.0; R Core Team, 2023) using the package *mgcv* (Version 1.9.1) and following model-fitting procedures outlined by Wieling (2018). To assess model results, we used summary statistics and visualized nonlinear patterns using the package *itsadug* (Version 2.4.1; van Rij et al., 2022). As our experimental protocol did not require the participants to pass the hearing screening, we validated our results by rerunning all hypothesis-testing (group-difference) models on individuals with none to mild hearing impairment (19 IwPD, 18 CS). This did not change any results in terms of group differences, and we therefore report results based on participants regardless of their hearing status.

Results

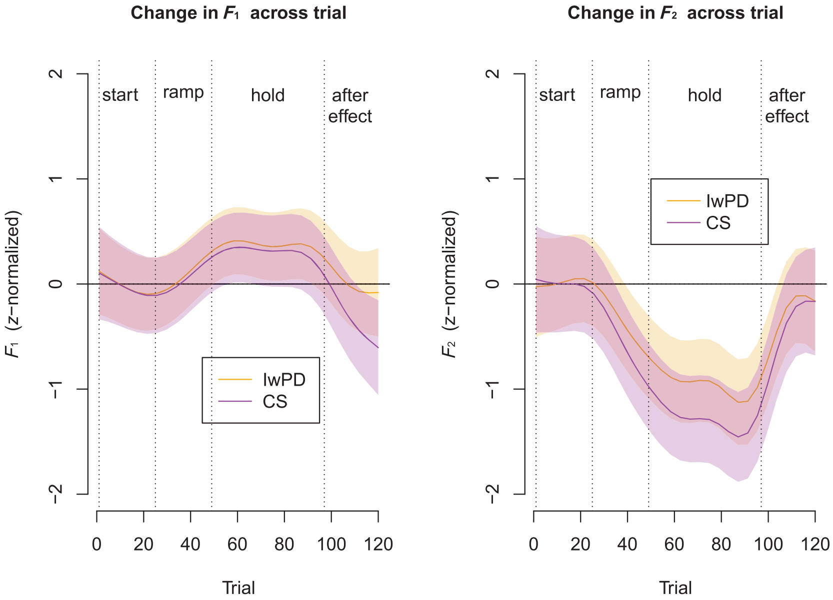
Adaptive Responses to Predictable Vowel Formant Perturbation

Formants and Jaw Height

At the group level, including all participants, there was a significant effect of trial on all three measures: F_1 ($p_{\text{fdr}} < .001$), F_2 ($p_{\text{fdr}} < .001$), and JAW_y ($p_{\text{fdr}} = .004$). Specifically, the participants responded to the consistent upward perturbation (F_1 decrease, F_2 increase) by raising their F_1, lowering their F_2, and raising their jaw across the trials.

There were no significant differences in adaptive responses between IwPD and CS in F_1 ($p_{\text{fdr}} = .29$), F_2 ($p_{\text{fdr}} = .21$), or JAW_y ($p_{\text{fdr}} = .29$). Figure 4 illustrates changes in the acoustic measures across trials, separated by participant group. Figure 5 illustrates changes in jaw height across trials. Note that this type of visualization includes the uncertainty about the intercept and constant group differences. As a consequence, most patterns overlap, to a large extent, with the x-axis, despite the nonlinear pattern itself being highly certain. The four stages of the experiment

Figure 4. Change across trial in F_1 (left) and F_2 (right). CS = control speakers; IwPD = individuals with Parkinson's disease.



(start, ramp, hold, after-effect) have been added to the figures to improve the clarity of interpretation and allow for comparison with prior studies.

Formants and All Kinematic Measures

At the group level, including the subgroup of participants with a full sensor set, there was a significant effect of trial on F_1 ($p_{\mathrm{fdr}} < .001$), F_2 ($p_{\mathrm{fdr}} < .001$), TT_x ($p_{\mathrm{fdr}} = .01$), TT_y ($p_{\mathrm{fdr}} = .01$), and TB_y ($p_{\mathrm{fdr}} < .001$), but not on TB_x ($p_{\mathrm{fdr}} = .13$), JAW_x ($p_{\mathrm{fdr}} = .13$), or JAW_y ($p_{\mathrm{fdr}} = .16$). Specifically, acoustically, the participants raised their F_1 and lowered their F_2. Kinematically, the tongue was more posterior and lower.

There was no significant difference in adaptive responses between IwPD and CS in any of the acoustic or kinematic

Figure 5. Change across trial in jaw height (JAW_y). CS = control speakers; IwPD = individuals with Parkinson's disease.

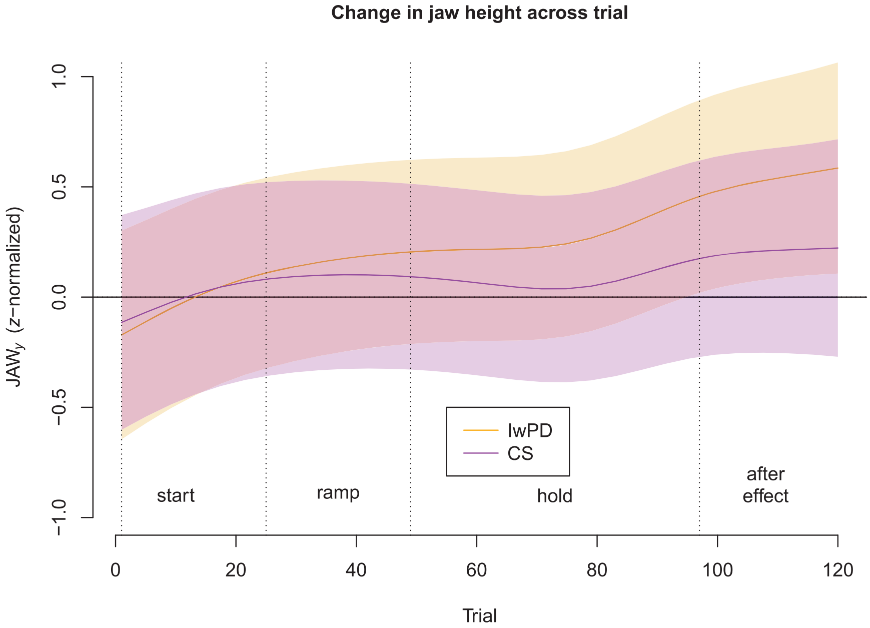
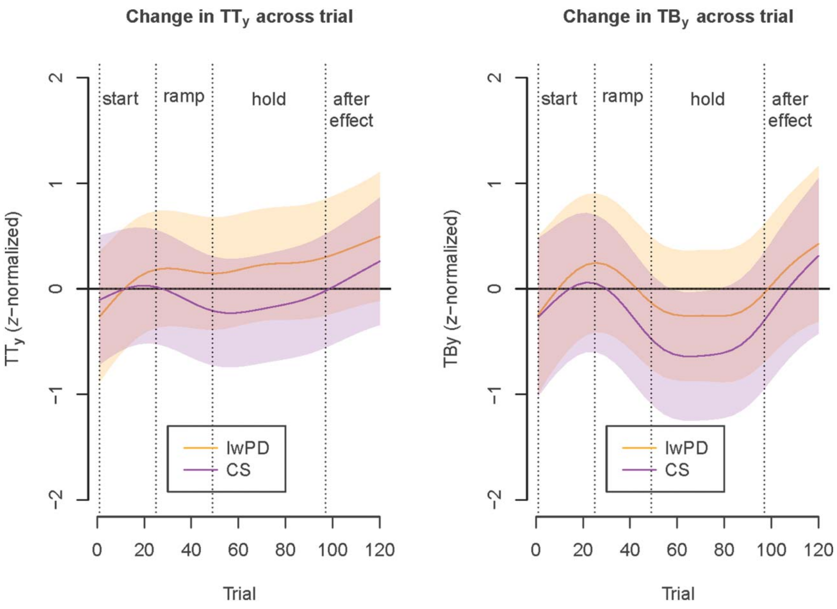


Figure 6. Change across trial for tongue body height. TT_y = tongue tip height; TB_y = tongue body height; CS = control speakers; IwPD = individuals with Parkinson's disease.



measures: F_1 (p_{fdr} = .93), F_2 (p_{fdr} = .97), TT_x (p_{fdr} = .97), TT_y (p_{fdr} = .37), TB_x (p_{fdr} = .97), TB_y (p_{fdr} = .66), JAW_x (p_{fdr} = .97), or JAW_y (p_{fdr} = .50). Figure 6 illustrates the change across trials for tongue height (the tongue was chosen as the target articulator for the production of vowels; changes in tongue tip height are depicted on the left, and changes in tongue body height are depicted on the right).

Reflexive Responses to Unexpected Vowel Formant Perturbation

Difference Between IwPD and CS: Formants and Jaw Height

For the upward perturbed condition, including all participants, there was no significant differences between IwPD and CS when modeling the change across the vowel trajectory in F_1 (p_{fdr} = .053), F_2 (p_{fdr} = .64), or JAW_y (p_{fdr} = .41). For the downward perturbed condition, there was no significant differences between IwPD in F_1 (p_{fdr} = .07) or JAW_y (p_{fdr} = .09), but there was a significant difference in the F_2 trajectory (p_{fdr} = .004), with IwPD showing a reduced and later response. Figure 7 displays the change in vowel trajectory for F_2 and difference plots for the two perturbed conditions. As the standard time window for assessing the involuntary compensatory response is 120–240 ms, we have added vertical dotted lines to the graphs corresponding to that window. The extremely low values at the beginning of each plot are not a result of the perturbation but rather the effect of the preceding consonant, which affects the vowel formants.

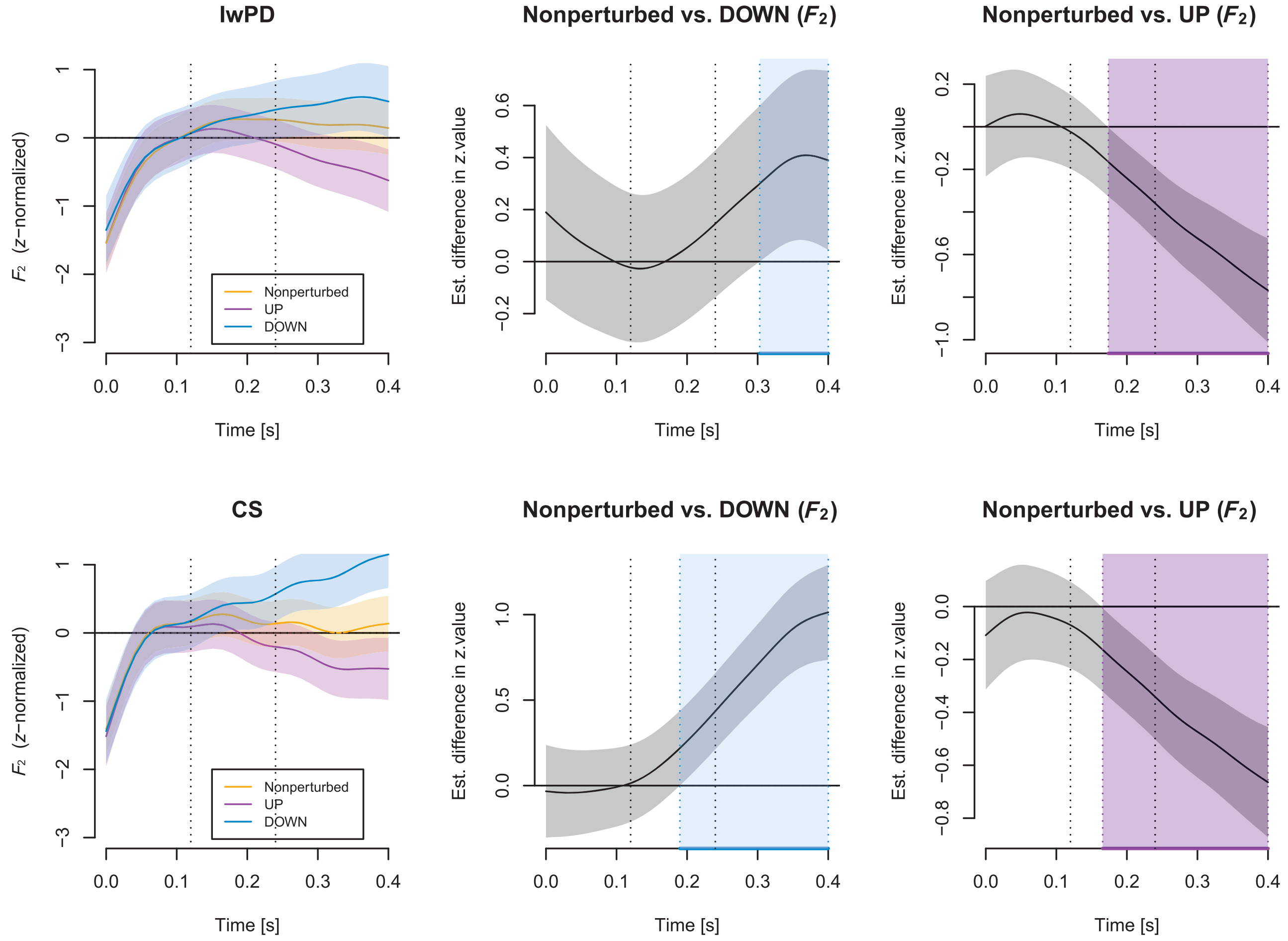
Difference Between IwPD and CS: Formants and All Kinematic Measures

For the upward perturbed condition, including only the participants with a full sensor set, there were no significant differences between IwPD and CS in any measure (all *p*s > .1). For the downward perturbed condition, there was a significant difference between IwPD and CS in TB_y (p_{fdr} = .007), with IwPD showing a smaller increase in tongue body height through vowel trajectory. There were no significant differences in other acoustic (F_1: p_{fdr} = .58, F_2: p_{fdr} = .08) or kinematic (TT_x: p_{fdr} = .81, TT_y: p_{fdr} = .1, TB_x: p_{fdr} = .59, JAW_x: p_{fdr} = .31, JAW_y: p_{fdr} = .12) measures. Figure 8 displays the change in vowel trajectory for the tongue body height.

Early Versus Late Time Windows

To allow comparability with earlier studies and to assess the nonsignificant trends from the main model, we conducted a follow-up analysis on formant trajectories for early (120–240 ms) and late (300–400 ms) time windows. These time windows, which are discussed in more detail in the Fast Correction for Vowel Formants Is Impaired in IwPD section, are thought to capture the involuntary and voluntary responses to the perturbation. For the upward perturbation, these models revealed a significant difference in F_1 between groups for the early time window (p_{fdr} = .005), but not late time window (p = .3). Conversely, for the downward perturbation, a significant difference was found in F_1 for the late time window (p_{fdr} = .03), but not for the early time window (p_{fdr} > .05). These results seemingly

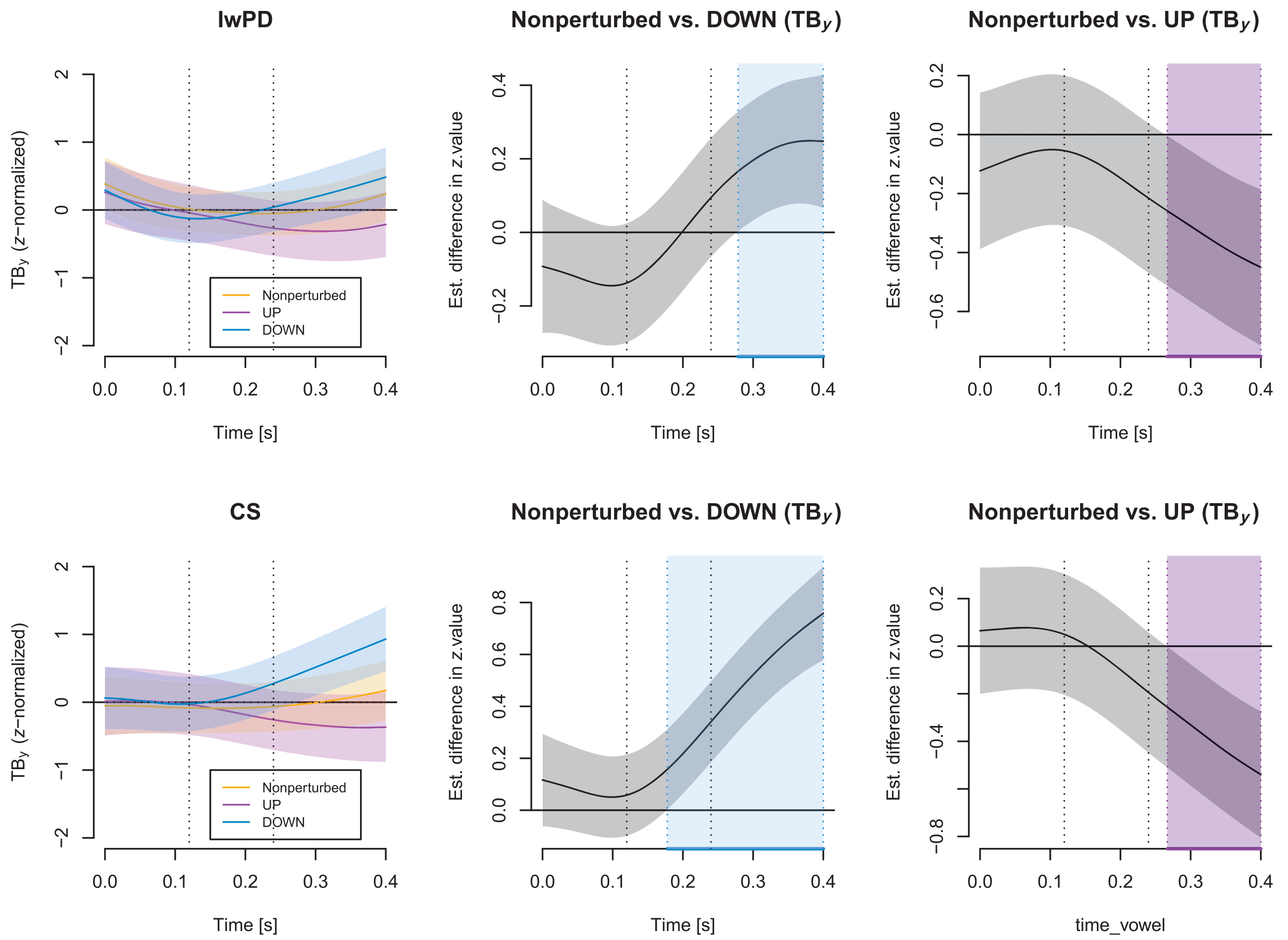
Figure 7. Left: Change in F_2 across the first 400 ms of the vowel for the group of individuals with Parkinson's disease (IwPD; upper) and control speakers (CS; lower) in the three conditions. Vertical dotted lines represent the time window of 120–240 ms. Middle: Difference between nonperturbed and downward perturbed conditions for IwPD (upper) and CS (lower). Right: Difference between nonperturbed and upward perturbed conditions for IwPD (upper) and CS (lower). The colored lines and shading in the middle and right plots represent the time window of significant difference; vertical dotted lines represent the time window of 120–240 ms.



(partly) oppose the results of the main model, which found no significant differences in F_1 trajectories between groups for either upward or downward perturbation, although both showed a trend toward compensation prior to correcting for multiple comparisons (p = .04 for the upward perturbation, p = .05 for the downward perturbation). Upon closer reflection, there are multiple reasons behind this discrepancy. For the upward perturbation, CS were earlier to compensate than IwPD, which led to a significant difference in the early window. However, both groups compensated in the late time window, leading to no significant differences between the trajectories of the two groups. For the downward perturbation, the CS group did seemingly start compensating earlier than the IwPD group, but the difference between the trajectories was not strong enough to be statistically significant in the early time window (as indicated by $p_{\text{fdr}} > .05$). In the late time window, however, the trend did become statistically significant, as IwPD compensated but to a lesser extent than CS.

For F_2, no significant differences were found for either perturbation direction or time window (all ps > .1). This matches the results of the main model for the upward perturbation, which yielded no significant differences between groups. However, it opposes the results from the downward perturbation, where IwPD compensated later than CS. This is likely due to the chosen windows of analysis: As also seen in Figure 7, CS only start compensating at around 190 ms. Consequently, there are no differences in compensation for a large majority of the "early" window (120–240 ms). In the "late" window (300–400 ms), both IwPD and CS are compensating, shown by the nonsignificant "late" model. Unlike the main model, which accounts

Figure 8. Left: Change in tongue body height (TB_y) across the first 400 ms of the vowel for the group of individuals with Parkinson's disease (IwPD; upper) and control speakers (CS; lower) in the three conditions. Vertical dotted lines represent the time window of 120–240 ms. Middle: Difference between nonperturbed and downward perturbed conditions for IwPD (upper) and CS (lower). Right: Difference between nonperturbed and upward perturbed conditions for IwPD (upper) and CS (lower). The colored lines and shading in the middle and right plots represent the time window of significant difference; vertical dotted lines represent the time window of 120–240 ms.



for the full vowel trajectory, the two windows do not account for the time frame between 240 and 300 ms, where CS already show significant compensation, but IwPD do not. Table 3 summarizes the results from the adaptive (see the Adaptive Responses to Predictable Vowel Formant Perturbation section) and reflexive (see the Reflexive Responses to Unexpected Vowel Formant section) tasks.

Discussion

The present study investigated auditory feedback integration for vowel formants in IwPD compared to CS. By measuring the adaptive and reflexive responses in both the acoustic dimension (as standard in the field) and the kinematic dimension (measuring tongue and jaw backness and height using EMA, as a novel addition), we aimed to gain a better understanding of how auditory feedback integration and motor execution contribute to articulatory impairments. For both the predictable and unexpected formant perturbation tasks, we conducted two analyses: one on the full set of participants, including acoustic measures (F_1 and F_2) and jaw height (JAW_y), and one on the subset of participants with all sensors, thus including both acoustic measures and kinematic measures for the jaw, tongue tip, and tongue back backness and height.

Motor Learning for Vowel Formants Is Preserved in IwPD

The first task was a predictable auditory formant perturbation task, capturing adaptive responses to measure the extent to which IwPD can adapt their sensorimotor plans when their auditory feedback for formants is consistently

Table 3. Summary of main group-level results from the adaptive and reflexive auditory feedback perturbation tasks.

Measure	*edf*	*F* value	p_{fdr} value
Adaptive: formants and jaw height (33 IwPD, 25 CS)			
F_1	4.33	1.02	.29
F_2	3.85	1.68	.21
JAW$_y$	2.00	1.39	.29
Adaptive: all acoustic and kinematic measures (15 IwPD, 14 CS)			
F_1	2.00	0.46	.92
F_2	2.00	0.15	.97
TT$_x$	2.00	0.06	.97
TT$_y$	3.79	1.59	.37
TB$_x$	2.00	0.18	.97
TB$_y$	3.21	0.99	.66
JAW$_x$	2.00	0.03	.97
JAW$_y$	2.00	1.26	.50
Reflexive: formants and jaw height (23 IwPD, 22 CS)			
F_1 up	2.02	3.22	.05
F_2 up	2.00	0.51	.64
JAW$_y$ up	2.02	1.01	.41
F_1 down	2.01	2.93	.07
F_2 down	2.09	5.76	.004*
JAW$_y$ down	3.16	2.12	.09
Reflexive: all acoustic and kinematic measures (12 IwPD, 11 CS)			
F_1 up	2.02	2.32	.15
F_2 up	2.02	1.88	.22
TT$_x$ up	2.05	2.64	.12
TT$_y$ up	2.03	0.08	.93
TB$_x$ up	2.03	1.63	.27
TB$_y$ up	2.03	2.31	.15
JAW$_x$ up	2.02	2.01	.20
JAW$_y$ up	2.02	1.72	.25
F_1 down	2.06	0.73	.58
F_2 down	2.12	3.15	.08
TT$_x$ down	2.02	0.24	.81
TT$_y$ down	2.09	2.99	.10
TB$_x$ down	2.04	0.61	.59
TB$_y$ down	3.43	4.01	.007*
JAW$_x$ down	2.69	1.36	.31
JAW$_y$ down	3.23	2.13	.12

Note. All results indicate the summary of the main smooths comparing individuals with Parkinson's disease (IwPD) and control speakers (CS). Significant differences have been marked with an asterisk (*). *edf* = effective degrees of freedom; fdr = false discovery rate; F_1 = first formant; F_2 = second formant; JAW$_y$ = jaw height; TT$_x$ = tongue tip backness; TT$_y$ = tongue tip height; TB$_x$ = tongue back backness; TB$_y$ = tongue back height; JAW$_x$ = jaw backness; down = downward perturbation; up = upward perturbation.

perturbed. Overall, we found no differences between IwPD and CS. This was the case for both the acoustically measured responses, corroborating the results of the study by Abur et al. (2021), and the kinematically measured responses, carried out for the first time. Specifically, on the acoustic level, the participants in both groups responded to a decrease in F_1 and an increase in F_2 by increasing their F_1 and decreasing their F_2, respectively (effectively making their vowel sound more /ɑ/-like).

On the kinematic level, we expected that successful adaptation—shown in an acoustically measurable and perceptually audible shift from /ɛ/ to /ɑ/—would result in a lower and more posterior tongue position, as well as a lower jaw. While the tongue indeed lowered (see Figure 6), the jaw was slightly raised, indicating a more closed vowel. On the one hand, this finding could align with prior results of Max et al. (2003), who found motor-equivalent adaptation in their group of speakers. On the other hand, this could “simply” confirm saturation effects for the vowel /a/, wherein a lot of jaw movement is needed prior to audible acoustic differences (Perkell & Cohen, 1989). To determine whether one or both explanations are suitable, further kinematics analyses are needed, including analyses that also use kinematically defined boundaries based on individual articulatory gestures. For the current analysis, kinematic data were extracted based on acoustic vowel annotations to allow for comparability with prior studies. However, this might have obscured some kinematic patterns, as the start and the end of articulatory gestures do not correspond to the acoustics.

Regardless, in our analysis, IwPD and CS showed similar acoustic and kinematic strategies to adapt to the perturbation. This is highly relevant, as it confirms that IwPD adapt to the perturbation using articulatory strategies similar to those of CS: In other words, they do not (need to) use compensatory movements to achieve the desired adaptation (as is sometimes the case when IwPD attempt to achieve changes in acoustic vowel contrast; see Mefferd & Dietrich, 2019). Our results therefore indicate that IwPD on medication seem able to integrate auditory feedback for articulation, reliably update their sensorimotor maps, and also successfully execute the motor movements necessary to enact the acoustic change in similar manner to that of CS. This result corroborates previous reports from motor literature that motor learning based on visual feedback (Venkatakrishnan et al., 2011) and tactile feedback (Olson et al., 2019) is preserved in IwPD on levodopa. Results from the predictable auditory formant perturbation task therefore do not help explain the articulation impairments of IwPD on medication.

Fast Correction for Vowel Formants Is Impaired in IwPD

The second task was an unexpected formant perturbation task, which aimed to track reflexive responses and measure the extent to which participants instantly correct perceived errors in their auditory feedback within a trial. On the acoustic level, when the formants were suddenly shifted upward, resulting in a perceived /ɪ/, we found no significant differences between IwPD and CS. This was likewise the case on the kinematic level, as there were no significant differences between groups in the measured tongue and/or jaw trajectory. Conversely, our follow-up acoustic analysis of early (120–240 ms) and late (300–400 ms) time windows revealed significant differences in F_1 between groups for the early time window. This difference was driven by CS compensating earlier than IwPD.

When the formants were suddenly shifted downward, resulting in a perceived /ɑ/, there was a significant difference between IwPD and CS in the F_2 trajectory when the data of all participants were included. The same pattern was visible but did not reach significance when the data of only the subgroup of participants (12 IwPD, 11 CS) were used. Kinematically, the downward perturbation did show a significant difference in tongue body height (for the subgroup of participants who had tongue body information), confirming the pattern.

The difference between the results of our study and those of Mollaei et al. (2016) and Abur et al. (2021) can thus partly be explained by the different chosen analysis time windows following perturbation onset. While Mollaei et al. looked at the time window of 300–400 ms, capturing the voluntary articulatory response, Abur et al. looked at the window between 120 and 240 ms, capturing the involuntary articulatory response. The analyzed time window is important to consider, as it captures different aspects of sensorimotor processing (Guenther, 2016; Hain et al., 2000; Tourville et al., 2008): The early involuntary response is presumed to be subconscious and generated by the auditory feedback control subsystem, while the late voluntary response is more likely to involve feedforward control mechanisms. The delay in the auditory feedback controller also includes the time it takes for the auditory error to be transferred to the motor cortex for a corrective movement to be performed (Guenther, 2016). In the case of IwPD, any processing delays in the motor cortex may result in later latencies of the response. This would be supported by prior studies showing reduced activation in the motor cortex but increased activation in the auditory cortex during speech production in IwPD (see a review by Contreras-Ruston et al., 2025).

In our case, using generalized additive modeling allowed us to assess the entire trajectory (as opposed to averaging within a certain time window) and showed that the reduction of the response in the downward perturbed condition is already visible in an early time window, but it becomes more apparent in the later time window. This, however, might not immediately be detectable when aggregating data (necessary for statistical techniques, such as the two-way analysis of variance used in the studies of Abur et al. [2021] and Mollaei et al. [2016]). Future studies should therefore analyze the entire trajectory of the vowel of interest, to ensure that they capture any “late” responses by IwPD that may be driven by motor execution or auditory processing difficulties.

Furthermore, it is not entirely surprising that there was a difference in responses between upward and downward perturbations. A prior study by Kothare et al. (2020) found that the direction of the shift determined the magnitude of the response, with more compensation found for a shift toward lower vowels (in our case: /ɛ/ to /ɑ/) than for a shift toward higher vowels (in our case: /ɛ/ to /ɪ/). This is confirmed in our results. Kothare et al. propose a few possible explanations, including a trade-off between perceived errors in auditory and somatosensory feedback and categorical perception. For the latter, a bigger compensation for the downward perturbation follows logically when considering the Dutch vowel space, where /ɛ/ and /ɪ/ are closer than /ɛ/ and /ɑ/ (Adank et al., 2004). The direction of the shift can also explain why our study results partly align with Mollaei et al. (2016) but not Abur et al. (2021). Although both studies used a 30% increase in F_1, Mollaei et al. shifted formants from /ɛ/ to /ɑ/, while Abur et al. shifted formants from /ɪ/ to /ɛ/. Conversely, in one prior study investigating individuals with cerebellar degeneration (Parrell et al., 2017), the perturbation direction in a reflexive task did not play a role in explaining group differences, even though responses overall were greater for the downward than upward perturbation in the vowel space (as in our study).

In cases of both directions of the perturbations, visualizations and analyses thus indicated that IwPD responded to a lesser degree and at a later time window compared to CS. As the difference between groups is present in the acoustics and the kinematics for the reflexive feedback perturbation task, it is likely that the delayed response is partly also due to increased muscle rigidity and slowing of tongue movements in IwPD (Kuruvilla-Dugdale et al., 2020). In other words, we cannot be certain whether IwPD are slower to integrate auditory feedback or are instead slower in translating the new input into immediate motor commands. This distinction, however, remains difficult to untangle. On the one hand, future studies should assess both auditory and somatosensory feedback impairments in the same group of IwPD in order to determine whether changes in the articulatory subsystem are indeed more linked to somatosensory feedback impairments rather than auditory feedback impairments, as has recently been suggested by Behroozmand et al. (2025). On the other hand, perturbation data should also be complemented by more extensive oromotor assessments, for example, by testing the tactile acuity of the tongue (Chen & Watson, 2017) or the tongue range of motion (e.g., Lazarus et al., 2014).

Implications for Mechanisms Underlying Articulation Impairments in IwPD

Our findings indicate that although immediate error correction on the basis of auditory feedback is impaired in IwPD on medication compared to CS, IwPD are able to detect the auditory error and learn on the basis of a continuously detected error. This therefore contradicts the presumption that hypokinetic dysarthria may result from speech sound maps that deteriorate due to misprocessed auditory feedback (Arnold et al., 2014; Moreau & Pinto, 2019), at least for articulatory impairments. Note, however, that this is probably not the case for impairments on the laryngeal level. The latter, which are more likely to occur in the earlier stages of the disease, were not covered in the current study.

In a recent article by Manes et al. (2024), the authors attribute reduced speech movements in IwPD specifically to impairments in the initiation circuit, a component of the feedforward control system (i.e., the issue lies in the initiation and scaling of speech movements). In their view, IwPD off medication "rely more heavily on sensory feedback control to compensate for feedforward control deficits" (Manes et al., 2024, p. 12), while IwPD on medication show a better functioning of feedforward control, as levodopa facilitates the initiation of speech movements. Kinematically, this is in line with at least one prior study showing that vocalic tongue body movements are more flexible on medication (Thies et al., 2021) and with the finding that bradykinesia is among the symptoms positively affected by levodopa (e.g., Bologna et al., 2020). It does not, however, exclude other issues with articulator movements, as IwPD tend to show reduced tongue muscle force compared to controls even on levodopa (e.g., De Letter et al., 2003; Solomon et al., 1995), and it also does not fully explain articulatory impairments of IwPD on medication.

Our study showed intact motor learning based on auditory feedback for formants, thus confirming the notion that feedforward control of IwPD on medication functions well. However, this does not exclude the possibility that impairments in the initiation component of the feedforward control circuit contribute to articulation difficulties. Specifically, results from our unexpected auditory feedback perturbation indicate that IwPD may be capable of integrating auditory feedback for formants but are slower at doing so. Looking at the DIVA model, as discussed by Manes et al. (2024), an overreliance on auditory feedback would result in overexaggerated responses in the reflexive perturbation task, which is not the case in our study. Instead, we see later responses, which could mean a delay in movement initiation (i.e., issues in the initiation circuit of feedforward control), difficulties in movement execution (i.e., issues in the sending of commands from the articulator map to articulator musculature), or a delay in auditory feedback integration (i.e., issues in detecting auditory error in a timely manner). Detangling these aspects, however, is beyond the scope of this study.

Limitations

The current study was the first to assess speech sensorimotor processing in IwPD through both acoustic and kinematic methods. It does, however, also suffer from some limitations. First, while the number of participants included in the study is larger than that of most perturbation and kinematic studies, especially the group of IwPD remains heterogenous due to large individual variability found in

PD. This heterogeneity also extends to a large range in participant ages (54–81 years) and hearing status, all of which contribute to a more ecologically representative sample but also one that is more difficult to analyze. We do, however, account for this with an age- and sex-matched control group. Second, placing EMA sensors on the tongue body is challenging, and we could not obtain information on the tongue body movement for many participants. As this is where we would expect most change to happen and is most relevant for vowels, we recommend any future studies to opt for only one sensor placed on the middle of the tongue. Third, differences between groups were captured with different acoustic and kinematic markers depending on the perturbation direction and were seemingly larger for the downward perturbation: As we only induced an upward perturbation for the predictable perturbation task, we cannot know whether any group differences would reveal themselves with a predictable downward perturbation. Finally, while auditory perturbation tasks provide a good opportunity to get a glimpse into potential speech sensorimotor processing impairments in IwPD, they provide only indirect information about auditory processing but not about somatosensory processing.

Conclusions

To conclude, our study showed that, while on medication, IwPD may show a reduced ability to integrate immediate auditory information for speech sensorimotor processing yet retain the ability to update their speech sensorimotor maps if the auditory feedback error remains predictable. This was apparent on both the acoustic and kinematic levels, indicating that the IwPD in our group did not show alternative compensatory articulatory strategies compared to CS. In this study, we chose to include IwPD on levodopa. While this makes it more difficult to draw inferences about the underlying impairments caused by PD, it increases ecological validity as it allows us to obtain an approximation of how speech motor control impairments might impact IwPD' daily lives. The results of our study thus indicate that issues with immediate error correction, stemming from either difficulties with motor execution or a slowing down of auditory feedback integration, could help explain articulation impairments in individuals with PD.

Data Availability Statement

Raw and preprocessed data cannot be made available due to restrictions imposed by our ethical approval. However, the data analysis, codes used to generate statistical models, statistical model outputs, and model visualizations (for figures in this article) have been made available at https://github.com/tejarebernik/pdformantperturbation.

Acknowledgments

This work was supported by funding from Dutch Research Council (NWO) Grants 019.2011.3.110.016, 016.144.049, and PGW.19.034 (awarded to Martijn Wieling) and ParkinsonNL Grant P2022-10 (awarded to Teja Rebernik). The authors would like to sincerely thank all participants in the study. They would furthermore like to acknowledge ParkinsonNext for their help with participant recruitment.

References

Abur, D., Enos, N. M., & Stepp, C. E. (2019). Visual analog scale ratings and orthographic transcription measures of sentence intelligibility in Parkinson's disease with variable listener exposure. *American Journal of Speech-Language Pathology, 28*(3), 1222–1232. https://doi.org/10.1044/2019_AJSLP-18-0275

Abur, D., Subaciute, A., Daliri, A., Lester-Smith, R. A., Lupiani, A. A., Cilento, D., Enos, N. M., Weerathunge, H. R., Tardif, M. C., & Stepp, C. E. (2021). Feedback and feedforward auditory–motor processes for voice and articulation in Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 64*(12), 4682–4694. https://doi.org/10.1044/2021_JSLHR-21-00153

Adank, P., van Hout, R., & Smits, R. (2004). An acoustic description of the vowels of Northern and Southern Standard Dutch. *The Journal of the Acoustical Society of America, 116*(3), 1729–1738. https://doi.org/10.1121/1.1779271

Anand, S., & Stepp, C. E. (2015). Listener perception of monopitch, naturalness, and intelligibility for speakers with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 58*(4), 1134–1144. https://doi.org/10.1044/2015_JSLHR-S-14-0243

Arnold, C., Gehrig, J., Gispert, S., Seifried, C., & Kell, C. A. (2014). Pathomechanisms and compensatory efforts related to Parkinsonian speech. *NeuroImage: Clinical, 4,* 82–97. https://doi.org/10.1016/j.nicl.2013.10.016

Behroozmand, R., Khoshhal Mollasaraei, Z., Nejati, V., Daliri, A., & Fridriksson, J. (2025). Vocal and articulatory speech control deficits in individuals with post-stroke aphasia. *Scientific Reports, 15*(1), Article 13350. https://doi.org/10.1038/s41598-025-96040-4

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B* (Methodological)*, 57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Boersma, P., & Weenink, D. (2019). *Praat: Doing phonetics by computer* (Version 6.3.15) [Computer program].

Bologna, M., Paparella, G., Fasano, A., Hallett, M., & Berardelli, A. (2020). Evolving concepts on bradykinesia. *Brain, 143*(3), 727–750. https://doi.org/10.1093/brain/awz344

Broadfoot, C. K., Abur, D., Hoffmeister, J. D., Stepp, C. E., & Ciucci, M. R. (2019). Research-based updates in swallowing and communication dysfunction in Parkinson disease: Implications for evaluation and management. *Perspectives of the*

ASHA Special Interest Groups, 4(5), 825–841. https://doi.org/10.1044/2019_PERS-SIG3-2019-0001

Cai, S., Boucek, M., Ghosh, S. S., Guenther, F. H., & Perkell, J. S. (2008). A system for online dynamic perturbation of formant trajectories and results from perturbations of the Mandarin triphthong /iau/. In R. Sock, S. Fuchs, & Y. Laprie (Eds.), *Proceedings of the 8th International Seminar on Speech Production* (ISSP 2008) (pp. 65–68). INRIA.

Cai, S., Ghosh, S. S., Guenther, F. H., & Perkell, J. S. (2010). Adaptive auditory feedback control of the production of formant trajectories in the Mandarin triphthong /iau/ and its pattern of generalization. *The Journal of the Acoustical Society of America, 128*(4), 2033–2048. https://doi.org/10.1121/1.3479539

Caligiuri, M. P. (1987). Labial kinematics during speech in patients with Parkinsonian rigidity. *Brain, 110*(4), 1033–1044. https://doi.org/10.1093/brain/110.4.1033

Carignan, C. (2022). *Praat script for automatic formant optimization* [Computer software]. https://github.com/ChristopherCarignan/formant-optimization

Chen, Y.-W., & Watson, P. J. (2017). Speech production and sensory impairment in mild Parkinson's disease. *The Journal of the Acoustical Society of America, 141*(5), 3030–3041. https://doi.org/10.1121/1.4980138

Clark, J. P., Adams, S. G., Dykstra, A. D., Moodie, S., & Jog, M. (2014). Loudness perception and speech intensity control in Parkinson's disease. *Journal of Communication Disorders, 51,* 1–12. https://doi.org/10.1016/j.jcomdis.2014.08.001

Contreras-Ruston, F., Duggirala, S. X., Wingbermühle, J., Navarra, J., & Kotz, S. A. (2025). Sensory feedback in Parkinson disease voice production: A systematic review. *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2025.02.039

Convey, R. B., Ihalainen, T., Liu, Y., Räsänen, O., Ylinen, S., & Penttilä, N. (2024). A comparative study of automatic vowel articulation index and auditory–perceptual assessments of speech intelligibility in Parkinson's disease. *International Journal of Speech-Language Pathology, 26*(5), 663–673. https://doi.org/10.1080/17549507.2023.2251725

Daliri, A., Chao, S.-C., & Fitzgerald, L. C. (2020). Compensatory responses to formant perturbations proportionally decrease as perturbations increase. *Journal of Speech, Language, and Hearing Research, 63*(10), 3392–3407. https://doi.org/10.1044/2020_JSLHR-19-00422

De Groote, E., De Keyser, K., Bockstael, A., Botteldooren, D., Santens, P., & De Letter, M. (2020). Central auditory processing in parkinsonian disorders: A systematic review. *Neuroscience & Biobehavioral Reviews, 113,* 111–132. https://doi.org/10.1016/j.neubiorev.2020.03.001

De Letter, M., Santens, P., & Van Borsel, J. (2003). The effects of levodopa on tongue strength and endurance in patients with Parkinson's disease. *Acta Neurologica Belgica, 103*(1), 35–38. https://pubmed.ncbi.nlm.nih.gov/12704981/

Forrest, K., Weismer, G., & Turner, G. S. (1989). Kinematic, acoustic, and perceptual analyses of connected speech produced by Parkinsonian and normal geriatric adults. *The Journal of the Acoustical Society of America, 85*(6), 2608–2622. https://doi.org/10.1121/1.397755

Gick, B., & Moisik, S. R. (2015). Quantal biomechanics in an embodied phonetics. *The Journal of the Acoustical Society of America, 137*(Suppl. 4), Article 2301. https://doi.org/10.1121/1.4920399

Goetz, C. G., Tilley, B. C., Shaftman, S. R., Stebbins, G. T., Fahn, S., Martinez-Martin, P., Poewe, W., Sampaio, C., Stern, M. B., Dodel, R., Dubois, B., Holloway, R., Jankovic, J., Kulisevsky, J., Lang, A. E., Lees, A., Leurgans, S., LeWitt, P. A., Nyenhuis, D., . . . LaPelle, N. (2008). Movement Disorder Society–sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): Scale presentation and clinimetric testing results: MDS-UPDRS: Clinimetric Assessment. *Movement Disorders, 23*(15), 2129–2170. https://doi.org/10.1002/mds.22340

Guenther, F. H. (2016). *Neural control of speech*. MIT Press. https://doi.org/10.7551/mitpress/10471.001.0001

Hain, T. C., Burnett, T. A., Kiran, S., Larson, C. R., Singh, S., & Kenney, M. K. (2000). Instructing subjects to make a voluntary response reveals the presence of two components to the audio-vocal reflex. *Experimental Brain Research, 130*(2), 133–141. https://doi.org/10.1007/s002219900237

Hartelius, L., & Svensson, P. (1994). Speech and swallowing symptoms associated with Parkinson's disease and multiple sclerosis: A survey. *Folia Phoniatrica et Logopaedica, 46*(1), 9–17. https://doi.org/10.1159/000266286

Hastie, T., & Tibshirani, R. (1990). Exploring the nature of covariate effects in the proportional hazards model. *Biometrics, 46*(4), 1005–1016. https://doi.org/10.2307/2532444

Ho, A. K., Bradshaw, J. L., & Iansek, R. (2000). Volume perception in Parkinsonian speech. *Movement Disorders, 15*(6), 1125–1131. https://doi.org/10.1002/1531-8257(200011)15:6<1125::aid-mds1010>3.0.co;2-r

Ho, A. K., Iansek, R., Marigliani, C., Bradshaw, J. L., & Gates, S. (1998). Speech impairment in a large sample of patients with Parkinson's disease. *Behavioural Neurology, 11*(3), 131–137. https://doi.org/10.1155/1999/327643

Houde, J. F., & Jordan, M. I. (1998). Sensorimotor adaptation in speech production. *Science, 279*(5354), 1213–1216. https://doi.org/10.1126/science.279.5354.1213

Houle, N., Feaster, T., Mira, A., Meeks, K., & Stepp, C. E. (2024). Sex differences in the speech of persons with and without Parkinson's disease. *American Journal of Speech-Language Pathology, 33*(1), 96–116. https://doi.org/10.1044/2023_AJSLP-22-00350

Jafari, Z., Kolb, B. E., & Mohajerani, M. H. (2020). Auditory dysfunction in Parkinson's disease. *Movement Disorders, 35*(4), 537–550. https://doi.org/10.1002/mds.28000

Johansson, I.-L., Samuelsson, C., & Müller, N. (2023). Consonant articulation acoustics and intelligibility in Swedish speakers with Parkinson's disease: A pilot study. *Clinical Linguistics & Phonetics, 37*(9), 845–865. https://doi.org/10.1080/02699206.2022.2095926

Karlawish, J., Cary, M., Moelter, S. T., Siderowf, A., Sullo, E., Xie, S., & Weintraub, D. (2013). Cognitive impairment and PD patients' capacity to consent to research. *Neurology, 81*(9), 801–807. https://doi.org/10.1212/WNL.0b013e3182a05ba5

Kearney, E., Giles, R., Haworth, B., Faloutsos, P., Baljko, M., & Yunusova, Y. (2017). Sentence-level movements in Parkinson's disease: Loud, clear, and slow speech. *Journal of Speech, Language, and Hearing Research, 60*(12), 3426–3440. https://doi.org/10.1044/2017_JSLHR-S-17-0075

Kim, Y., & Choi, Y. (2017). A cross-language study of acoustic predictors of speech intelligibility in individuals with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 60*(9), 2506–2518. https://doi.org/10.1044/2017_JSLHR-S-16-0121

Kothare, H., Raharjo, I., Ramanarayanan, V., Ranasinghe, K., Parrell, B., Johnson, K., Houde, J. F., & Nagarajan, S. S. (2020). Sensorimotor adaptation of speech depends on the direction of auditory feedback alteration. *The Journal of the Acoustical Society of America, 148*(6), 3682–3697. https://doi.org/10.1121/10.0002876

Kuo, C., & Berry, J. (2023). The relationship between acoustic and kinematic vowel space areas with and without normalization for speakers with and without dysarthria. *American Journal of*

Speech-Language Pathology, 32(4S), 1923–1937. https://doi.org/10.1044/2023_AJSLP-22-00158

Kuruvilla-Dugdale, M., Salazar, M., Zhang, A., & Mefferd, A. S. (2020). Detection of articulatory deficits in Parkinson's disease: Can systematic manipulations of phonetic complexity help? *Journal of Speech, Language, and Hearing Research, 63*(7), 2084–2098. https://doi.org/10.1044/2020_JSLHR-19-00245

Lazarus, C. L., Husaini, H., Jacobson, A. S., Mojica, J. K., Buchbinder, D., Okay, D., & Urken, M. L. (2014). Development of a new lingual range-of-motion assessment scale: Normative data in surgically treated oral cancer patients. *Dysphagia, 29*(4), 489–499. https://doi.org/10.1007/s00455-014-9534-9

Lee, J., Shaiman, S., & Weismer, G. (2016). Relationship between tongue positions and formant frequencies in female speakers. *The Journal of the Acoustical Society of America, 139*(1), 426–440. https://doi.org/10.1121/1.4939894

Lima, C. F., Garrett, C., & Castro, S. L. (2013). Not all sounds sound the same: Parkinson's disease affects differently emotion processing in music and in speech prosody. *Journal of Clinical and Experimental Neuropsychology, 35*(4), 373–392. https://doi.org/10.1080/13803395.2013.776518

Lindblom, B. E. F., & Sundberg, J. E. F. (1971). Acoustical consequences of lip, tongue, jaw, and larynx movement. *The Journal of the Acoustical Society of America, 50*(4B), 1166–1179. https://doi.org/10.1121/1.1912750

Manes, J. L., Bullock, L., Meier, A. M., Turner, R. S., Richardson, R. M., & Guenther, F. H. (2024). A neurocomputational view of the effects of Parkinson's disease on speech production. *Frontiers in Human Neuroscience, 18,* Article 1383714. https://doi.org/10.3389/fnhum.2024.1383714

Max, L., Wallace, M. E., & Vincent, I. (2003). Sensorimotor adaptation to auditory perturbations during speech: Acoustic and kinematic experiments. In M. J. Solé, D. Recasens, & J. Romero (Eds.), *Proceedings of the 15th International Congress of Phonetic Sciences (ICPhS-15)* (pp. 1053–1056). Futurgraphic.

McRae, P. A., Tjaden, K., & Schoonings, B. (2002). Acoustic and perceptual consequences of articulatory rate change in Parkinson disease. *Journal of Speech, Language, and Hearing Research, 45*(1), 35–50. https://doi.org/10.1044/1092-4388(2002/003)

Mefferd, A. S., & Dietrich, M. S. (2019). Tongue- and jaw-specific articulatory underpinnings of reduced and enhanced acoustic vowel contrast in talkers with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 62*(7), 2118–2132. https://doi.org/10.1044/2019_JSLHR-S-MSC18-18-0192

Miller, N. (2017). Communication changes in Parkinson's disease. *Practical Neurology, 17*(4), 266–274. https://doi.org/10.1136/practneurol-2017-001635

Mollaei, F., Shiller, D. M., Baum, S. R., & Gracco, V. L. (2016). Sensorimotor control of vocal pitch and formant frequencies in Parkinson's disease. *Brain Research, 1646,* 269–277. https://doi.org/10.1016/j.brainres.2016.06.013

Mollaei, F., Shiller, D. M., & Gracco, V. L. (2013). Sensorimotor adaptation of speech in Parkinson's disease. *Movement Disorders, 28*(12), 1668–1674. https://doi.org/10.1002/mds.25588

Moreau, C., & Pinto, S. (2019). Misconceptions about speech impairment in Parkinson's disease. *Movement Disorders, 34*(10), 1471–1475. https://doi.org/10.1002/mds.27791

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Olson, M., Lockhart, T. E., & Lieberman, A. (2019). Motor learning deficits in Parkinson's disease (PD) and their effect on training response in gait and balance: A narrative review. *Frontiers Neurology, 10,* Article 62. https://doi.org/10.3389/fneur.2019.00062

Olusanya, B. O., Davis, A. C., & Hoffman, H. J. (2019). Hearing loss grades and the International Classification of Functioning, Disability and Health. *Bulletin of the World Health Organization, 97*(10), 725–728. https://doi.org/10.2471/BLT.19.230367

Parrell, B., Agnew, Z., Nagarajan, S., Houde, J., & Ivry, R. B. (2017). Impaired feedforward control and enhanced feedback control of speech in patients with cerebellar degeneration. *Journal of Neuroscience, 37*(38), 9249–9258. https://doi.org/10.1523/JNEUROSCI.3363-16.2017

Perkell, J. S., & Cohen, M. H. (1989). An indirect test of the quantal nature of speech in the production of the vowels /i/, /a/ and /u/. *Journal of Phonetics, 17*(1–2), 123–133. https://doi.org/10.1016/S0095-4470(19)31517-7

Perkell, J. S., Cohen, M. H., Svirsky, M. A., Matthies, M. L., Garabieta, I., & Jackson, M. T. T. (1992). Electromagnetic midsagittal articulometer systems for transducing speech articulatory movements. *The Journal of the Acoustical Society of America, 92*(6), 3078–3096. https://doi.org/10.1121/1.404204

Perrier, P., & Fuchs, S. (2015). Motor equivalence in speech production. In M. A. Redford (Ed.), *The handbook of speech production* (pp. 223–247). Wiley. https://doi.org/10.1002/9781118584156.ch11

Pinto, S., Ozsancak, C., Tripoliti, E., Thobois, S., Limousin-Dowsey, P., & Auzou, P. (2004). Treatments for dysarthria in Parkinson's disease. *The Lancet Neurology, 3*(9), 547–556. https://doi.org/10.1016/S1474-4422(04)00854-3

Raines, C., & Mefferd, A. (2024). Disease-specific speech movement characteristics of the tongue and jaw. *Journal of Speech, Language, and Hearing Research, 68*(Suppl. 7), 3544–3557. https://doi.org/10.1044/2024_JSLHR-24-00351

Ravizza, S. M. (2003). Dissociating the performance of cortical and subcortical patients on phonemic tasks. *Brain and Cognition, 53*(2), 301–310. https://doi.org/10.1016/S0278-2626(03)00131-3

Rebernik, T., Jacobi, J., Jonkers, R., Noiray, A., & Wieling, M. (2021). A review of data collection practices using electromagnetic articulography. *Laboratory Phonology, 12*(1), Article 6. https://doi.org/10.5334/labphon.237

Rebernik, T., Jacobi, J., Tiede, M., & Wieling, M. (2021). Accuracy assessment of two electromagnetic articulographs: Northern Digital Inc. WAVE and Northern Digital Inc. VOX. *Journal of Speech, Language, and Hearing Research, 64*(7), 2637–2667. https://doi.org/10.1044/2021_JSLHR-20-00394

Rusz, J., Tykalová, T., Klempíř, J., Čmejla, R., & Růžička, E. (2016). Effects of dopaminergic replacement therapy on motor speech disorders in Parkinson's disease: Longitudinal follow-up study on previously untreated patients. *Journal of Neural Transmission, 123*(4), 379–387. https://doi.org/10.1007/s00702-016-1515-8

Schalling, E., Johansson, K., & Hartelius, L. (2018). Speech and communication changes reported by people with Parkinson's disease. *Folia Phoniatrica et Logopaedica, 69*(3), 131–141. https://doi.org/10.1159/000479927

Schneider, J. S., Diamond, S. G., & Markham, C. H. (1986). Deficits in orofacial sensorimotor function in Parkinson's disease. *Annals of Neurology, 19*(3), 275–282. https://doi.org/10.1002/ana.410190309

Schow, R. L. (1991). Considerations in selecting and validating an adult/elderly hearing screening protocol. *Ear and Hearing, 12*(5), 337–348. https://doi.org/10.1097/00003446-199110000-00006

Shetty, K., Krishnan, S., Thulaseedharan, J. V., Mohan, M., & Kishore, A. (2019). Asymptomatic hearing impairment frequently occurs in early-onset Parkinson's disease. *Journal of Movement Disorders, 12*(2), 84–90. https://doi.org/10.14802/jmd.18048

Skodda, S., Flasskamp, A., & Schlegel, U. (2010). Instability of syllable repetition as a model for impaired motor processing: Is Parkinson's disease a "rhythm disorder"? *Journal of Neural Transmission, 117*(5), 605–612. https://doi.org/10.1007/s00702-010-0390-y

Skodda, S., Grönheit, W., & Schlegel, U. (2012). Impairment of vowel articulation as a possible marker of disease progression in Parkinson's disease. *PLOS ONE, 7*(2), Article e32132. https://doi.org/10.1371/journal.pone.0032132

Skodda, S., Visser, W., & Schlegel, U. (2011). Vowel articulation in Parkinson's disease. *Journal of Voice, 25*(4), 467–472. https://doi.org/10.1016/j.jvoice.2010.01.009

Solomon, N., Lorell, D. M., Robin, D., Rodnitzky, R., & Luschei, E. S. (1995). Tongue strength and endurance in mild to moderate Parkinson's disease. *Journal of Medical Speech-Language Pathology, 3,* 15–26.

Stepp, C. E., Lester-Smith, R. A., Abur, D., Daliri, A., Noordzij, J. P., & Lupiani, A. A. (2017). Evidence for auditory–motor impairment in individuals with hyperfunctional voice disorders. *Journal of Speech, Language, and Hearing Research, 60*(6), 1545–1550. https://doi.org/10.1044/2017_JSLHR-S-16-0282

Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics, 17*(1–2), 3–45. https://doi.org/10.1016/S0095-4470(19)31520-7

Stipancic, K. L., & Tjaden, K. (2022). Minimally detectable change of speech intelligibility in speakers with multiple sclerosis and Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 65*(5), 1858–1866. https://doi.org/10.1044/2022_JSLHR-21-00648

Sussman, J. E., & Tjaden, K. (2012). Perceptual measures of speech from individuals with Parkinson's disease and multiple sclerosis: Intelligibility and beyond. *Journal of Speech, Language, and Hearing Research, 55*(4), 1208–1219. https://doi.org/10.1044/1092-4388(2011/11-0048)

Thies, T., Mücke, D., Dano, R., & Barbe, M. T. (2021). Levodopa-based changes on vocalic speech movements during prosodic prominence marking. *Brain Sciences, 11*(5), Article 594. https://doi.org/10.3390/brainsci11050594

Thies, T., Mücke, D., Geerts, N., Seger, A., Fink, G. R., Barbe, M. T., & Sommerauer, M. (2023). Compensatory articulatory mechanisms preserve intelligibility in prodromal Parkinson's disease. *Parkinsonism & Related Disorders, 112,* Article 105487. https://doi.org/10.1016/j.parkreldis.2023.105487

Thompson, A., & Kim, Y. (2019). Relation of second formant trajectories to tongue kinematics. *The Journal of the Acoustical Society of America, 145*(4), EL323–EL328. https://doi.org/10.1121/1.5099163

Thompson, A., & Kim, Y. (2024). Acoustic and kinematic predictors of intelligibility and articulatory precision in Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 67*(10), 3595–3611. https://doi.org/10.1044/2024_JSLHR-24-00153

Tourville, J. A., & Guenther, F. H. (2011). The DIVA model: A neural theory of speech acquisition and production. *Language and Cognitive Processes, 26*(7), 952–981. https://doi.org/10.1080/01690960903498424

Tourville, J. A., Reilly, K. J., & Guenther, F. H. (2008). Neural mechanisms underlying auditory feedback control of speech. *NeuroImage, 39*(3), 1429–1443. https://doi.org/10.1016/j.neuroimage.2007.09.054

Tykalova, T., Novotny, M., Ruzicka, E., Dusek, P., & Rusz, J. (2022). Short-term effect of dopaminergic medication on speech in early-stage Parkinson's disease. *npj Parkinson's Disease, 8*(1), Article 22. https://doi.org/10.1038/s41531-022-00286-y

van Rij, J., Hendriks, P., van Rijn, H., Baayen, R. H., & Wood, S. N. (2019). Analyzing the time course of pupillometric data. *Trends in Hearing, 23,* Article 2331216519832483. https://doi.org/10.1177/2331216519832483

van Rij, J., Wieling, M., Baayen, R. H., & van Rijn, H. (2022). *itsadug: Interpreting time series and autocorrelated data using GAMMs* (Version 2.4.1) [Computer software]. https://cran.r-project.org/web/packages/itsadug/

Venkatakrishnan, A., Banquet, J. P., Burnod, Y., & Contreras-vidal, J. L. (2011). Parkinson's disease differentially affects adaptation to gradual as compared to sudden visuomotor distortions. *Human Movement Science, 30*(4), 760–769. https://doi.org/10.1016/j.humov.2010.08.020

Walsh, B., & Smith, A. (2012). Basic parameters of articulatory movements and acoustics in individuals with Parkinson's disease. *Movement Disorders, 27*(7), 843–850. https://doi.org/10.1002/mds.24888

Weerathunge, H. R., Abur, D., Enos, N. M., Brown, K. M., & Stepp, C. E. (2020). Auditory–motor perturbations of voice fundamental frequency: Feedback delay and amplification. *Journal of Speech, Language, and Hearing Research, 63*(9), 2846–2860. https://doi.org/10.1044/2020_JSLHR-19-00407

Weerathunge, H. R., Tomassi, N. E., & Stepp, C. E. (2022). What can altered auditory feedback paradigms tell us about vocal motor control in individuals with voice disorders? *Perspectives of the ASHA Special Interest Groups, 7*(3), 959–976. https://doi.org/10.1044/2022_PERSP-21-00195

Whitfield, J. A., & Goberman, A. M. (2014). Articulatory–acoustic vowel space: Application to clear speech in individuals with Parkinson's disease. *Journal of Communication Disorders, 51,* 19–28. https://doi.org/10.1016/j.jcomdis.2014.06.005

Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics, 70,* 86–116. https://doi.org/10.1016/j.wocn.2018.03.002

Wood, S. N. (2017). *Generalized additive models: An introduction with R* (2nd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9781315370279

Zach, H., Dirkx, M. F., Roth, D., Pasman, J. W., Bloem, B. R., & Helmich, R. C. (2020). Dopamine-responsive and dopamine-resistant resting tremor in Parkinson disease. *Neurology, 95*(11), e1461–e1470. https://doi.org/10.1212/WNL.0000000000010316

Appendix

Questionnaire for Self-Assessment of Speech Impairment

The participants were asked whether they recognize or experience any of the following speech characteristics or difficulties. The two questions marked with an asterisk were repeated questions and only counted as a single answer.

Statement	Subsystem
I have difficulties with pronouncing of certain sounds and sound combinations.	Articulation
I frequently pronounce sounds inaccurately.	Articulation
I frequently mumble.	Articulation
My speech often sounds unclear.	Articulation
I often need to repeat myself to make myself understood.*	Articulation
I often speak more slowly to make myself understood.	Articulation
I find it difficult to make myself understood the first time I say something.*	Articulation
My voice often sounds flat and emotionless.	Phonation
My voice is often weak, as if I whisper or talk softly.	Phonation
My voice often sounds hoarse, as if I had a sore throat.	Phonation
My voice is often unstable.	Phonation
I find it difficult to produce a clear, loud voice.	Phonation
I often speak monotonously, with the same pitch and loudness.	Phonation
It takes me a lot of effort to speak.	Suprasegmental
I find it difficult to speak for a longer period of time.	Suprasegmental
I often speak slowly.	Suprasegmental
I often speak fast and stutter or stammer because of it.	Suprasegmental
I find it difficult to keep my speech tempo under control.	Suprasegmental
I find it difficult to put emphasis on the correct word or syllable.	Suprasegmental
I find it difficult to start a conversation because I struggle to find the right words.	Linguistic
I need to think a lot about the right words and lose my train of thought quickly.	Linguistic
I struggle to put my thoughts into words.	Linguistic
I find it difficult to make and keep eye contact with my collocutor.	Linguistic