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What Can Altered Auditory Feedback Paradigms Tell Us About Vocal Motor Control in Individuals With Voice Disorders?

Hasini R. Weerathunge,[a,b] Nicole E. Tomassi,[b,c] and Cara E. Stepp[a,b,d]

[a] Department of Biomedical Engineering, Boston University, MA [b] Department of Speech, Language, and Hearing Sciences, Boston University, MA [c] Graduate Program for Neuroscience, Boston University, MA [d] Department of Otolaryngology—Head and Neck Surgery, Boston University School of Medicine, MA

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ABSTRACT

Purpose: The goal of this review article is to provide a summary of the progression of altered auditory feedback (AAF) as a method to understand the pathophysiology of voice disorders. This review article focuses on populations with voice disorders that have thus far been studied using AAF, including individuals with Parkinson's disease, cerebellar degeneration, hyperfunctional voice disorders, vocal fold paralysis, and laryngeal dystonia. Studies using AAF have found that individuals with Parkinson's disease, cerebellar degeneration, and laryngeal dystonia have hyperactive auditory feedback responses due to differing underlying causes. In persons with PD, the hyperactivity may be a compensatory mechanism for atypically weak feedforward motor control. In individuals with cerebellar degeneration and laryngeal dystonia, the reasons for hyperactivity remain unknown. Individuals with hyperfunctional voice disorders may have auditory–motor integration deficits, suggesting atypical updating of feedforward motor control.

Conclusions: These findings have the potential to provide critical insights to clinicians in selecting the most effective therapy techniques for individuals with voice disorders. Future collaboration between clinicians and researchers with the shared objective of improving AAF as an ecologically feasible and valid tool for clinical assessment may provide more personalized therapy targets for individuals with voice disorders.

Voice is a feature unique to each individual that helps define and express one's personality, mood, and health. Disorders affecting the vocal apparatus can cause great difficulty in daily communication as they can manifest as the loss of modulation of pitch, loudness, and/or perceived voice quality. Voice disorders affect an estimated 3%–9% of the U.S. population (Ramig & Verdolini, 1998; Roy et al., 2005), as well as the large number of individuals who do not seek treatment and thus are not reported in point prevalence statistics (Cohen et al., 2012). Although extremely common, a wide range of etiologies may be associated with voice disorders, and much is unknown about their pathophysiology. Typical voice production depends on the respiratory subsystem (i.e., airflow and respiratory muscle strength), the laryngeal subsystem (i.e., laryngeal muscle strength, balance, coordination, and stamina), and their coordination with supraglottic resonatory structures (i.e., pharynx, oral cavity, and nasal cavity). A disturbance in one of the three subsystems of speech production or incoordination among the systems may lead to a voice disturbance. These disruptions can be due to organic, functional, and/or psychogenic causes, although the complementary relationships among these causes ensure that many voice disorders will have contributors from more than one etiological factor (Stemple et al., 2018; Verdolini et al., 2014). Recognizing associations among these factors may help in identifying the possible causes of the voice

Correspondence to Hasini R. Weerathunge: hasiniw@bu.edu. ***Disclosure:*** *The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.*

disorder and aid in the process of developing effective clinical intervention. However, it has been often observed that, even when an obvious cause is identified and treated, the voice problem may persist (e.g., an upper respiratory infection could be the initial cause of dysphonia, but poor or inefficient compensatory techniques may cause the dysphonia to persist long after the infection has resolved; American Speech-Language-Hearing Association, n.d.). These instances showcase that the underlying mechanisms causing voice disorders require more investigation. Many previous studies have investigated voice production in individuals with voice disorders via typical clinical evaluation (e.g., stroboscopy, acoustics, aerodynamics, auditory-perceptual judgments, and patient-reported outcome measures; Dastolfo-Hromack & Walsh, 2020; Rubin et al., 2014). However, these acoustic measures reflect the multiple underlying motor processes underlying speech production as well as any compensatory mechanisms in place to mitigate any deficits (Boone et al., 2005). Examination of the underlying processes of vocal motor control may aid in decoupling these effects.

The neurological commands for vocal production begin in the central nervous system and traverse through the peripheral nervous system to lower motor neurons to engage the larynx as well as the respiratory and supralaryngeal structures (Ludlow, 2005). The biomechanical components of vocal production involve airflow expelling from the lungs, causing the vocal folds to oscillate (see the works of Titze, 2000, and Zhang, 2016, for a review of the biomechanics of vocal production). The resulting vibration is then filtered through pharyngeal, oral, and nasal cavities to generate acoustic signals that are perceived by the auditory system. Likewise, the resulting vibrotactile sensations and proprioception of laryngeal structures are perceived by the somatosensory system (Jurgens, 2009; Parkinson et al., 2012). The Directions Into Velocities of Articulators (DIVA) model (Guenther, 2016) posits two interacting systems for the neural control of speech production: a feedback and feedforward control system. The feedback control system (using both auditory and somatosensory feedback) monitors and quickly corrects motor behaviors. Additionally, if there are persistent errors over multiple vocal productions, the feedforward control system updates its motor commands based on these feedback errors. Once the auditory targets for speech sounds are learned, the mature adult system relies on the feedforward system to produce stored motor programs, subsequently depending less on auditory feedback. Auditory feedback control continues to be important for monitoring and correcting errors during speech production; however, speech corrections occur at a relatively slower rate (100–150 ms; Burnett et al., 1997, 1998), so it is necessary to use established motor programs for fluent speech.

One way to assess vocal motor control is to artificially perturb the feedback provided to the system and monitor the response. Manipulating the somatosensory feedback associated with vocal productions tends to be difficult (i.e., applying anesthetics to vocal folds or physically perturbing larynx location), whereas altered auditory feedback (AAF) studies are noninvasive and comparatively easy to conduct. AAF paradigms may be used to modify acoustic features related to vocalization. Vocal fundamental frequency (vocal f_o; i.e., the acoustic correlate of pitch) and vocal sound pressure level (SPL; i.e., the acoustic correlate of loudness) are common candidates to study vocal motor control. In 1981, Elman introduced a new technique to study the influence of auditory feedback on vocal f_o control: Vocal responses to sudden, unpredictable auditory feedback perturbations were examined (*hereafter referred to as reflexive paradigms*), providing information about feedback error correction (Bauer & Larson, 2003; Bauer et al., 2006; Burnett et al., 1997, 1998; Elman, 1981). Later on, sustained and predictable perturbations to auditory feedback (*hereafter referred to as adaptive paradigms*) were used to examine how auditory feedback corrections are incorporated to feedforward commands when errors persist over multiple vocal productions (Behroozmand & Sangtian, 2018; Hawco & Jones, 2010; Keough & Jones, 2009; Scheerer et al., 2016). In response to both auditory reflexive and adaptive paradigms, adults with typical voices tend to produce compensatory vocal responses (i.e., responses that are in opposition to the perturbation; e.g., vocal f_o reflexive responses—Burnett et al., 1997, 1998, vocal SPL reflexive responses—Bauer et al., 2006; Larson et al., 2007, vocal f_o adaptive responses—Hawco & Jones, 2010; Keough & Jones, 2009). Reflexive compensatory response latencies are reported to be about 100 ms, and the reflexive compensatory response magnitudes tend to be relatively smaller in magnitude compared to the perturbation magnitude (Burnett et al., 1997, 1998). Adaptive compensatory response magnitudes also tend to be relatively smaller in magnitude compared to the perturbation (Katseff et al., 2012). There is evidence that the learned adjustments (i.e., adaptations) persist for subsequent trials even when the perturbation is removed (Jones & Munhall, 2000, 2002).

Currently, AAF is being used in a research capacity as a method to investigate underlying vocal motor control mechanisms in populations with voice disorders, but its clinical utility remains to be investigated. However, there is some evidence to suggest that AAF could also be used as a clinical intervention technique. In communication disorders such as stuttering, frequency altered and delayed auditory feedback have been used as clinical intervention techniques (Lincoln et al., 2006). Although there are no clinically approved therapies involving AAF techniques for dysphonic speech, recent research findings provide promising evidence that AAF could be employed as a potential clinical therapy. For example, the Lombard effect (i.e., increase of vocal intensity in the presence of masking noise in auditory feedback; Lane & Tranel, 1971; Zollinger & Brumm, 2011) has been used in several studies to increase vocal intensity in persons with Parkinson's disease (PD; Richardson et al., 2014; Stathopoulos et al., 2014) and in individuals with aphonia (Egan, 1975). Moreover, a recent study conducted in participants with typical vocal function showed that the presence of unpredictable variability in voice intensity auditory feedback can lead to increased harmonicity of voice during sustained phonation (Schenck et al., 2020). Results of another study carried out on participants with different voice qualities (i.e., breathy, typical, and pressed voice) showed that laryngeal resistance of individuals with a pressed voice pattern significantly increased when presented with masking noise as auditory feedback, whereas no significant differences were observed in individuals with typical or breathy voice quality (Grillo et al., 2010). Thus, it seems that individuals with pressed voice quality may be more susceptible to changes applied to auditory feedback via masking noise. However, the research is limited and much needs to be understood about the underlying causes of voice disorders before AAF-based clinical interventions can be proposed. Therefore, it is crucial that clinicians are informed about AAF techniques and current theoretical findings in AAF spanning populations with voice disorders, such that future investigations continue to investigate the relevance of AAF for theoretical and clinical issues surrounding vocal function.

In this review article, we reviewed studies that have thus far been conducted using AAF in populations with voice disorders, including individuals with PD, cerebellar degeneration (CD), hyperfunctional voice disorders (HVDs), vocal fold paralysis, and laryngeal dystonia (LD). The goal of this review article is to provide a summary of the findings, similarities, and variations in these AAF studies to provide perspective on what has been learned about the pathophysiology of voice disorders through the use of AAF. The following sections list AAF studies and their findings grouped by specific clinical population. See Table 1 for a summary of key papers and findings.

PD

Idiopathic PD is one of the fastest growing progressive neurodegenerative diseases in the world (Dorsey et al., 2018). Although research in the late 1950s identified striatal dopamine depletion as the major cause of the limb motor symptoms of PD, the presence of nonmotor features supports the involvement of other neurotransmitters and brain regions (Lim et al., 2009; Postuma et al., 2012; Willis et al., 2012). Eighty-nine percent of people with PD have voice disorders, characterized by reduced voice amplitude, monotone, breathy, and hoarse voice quality (Logemann et al., 1978). Studies have also reported abnormal perceptual processing of voice auditory feedback in PD (Clark et al., 2014; Troche et al., 2012), suggesting that input to the vocal motor control system is atypical, which might explain why some persons with PD (PwPD) fail to recognize that their voices are not loud enough to be heard by others (Clark et al., 2014; Critchley, 1981; Logemann et al., 1978). However, other similar studies have also reported no speech perception deficits in PD (Abur, Lupiani, et al., 2018; Dromey & Adams, 2000; Huang et al., 2016). These contradictory findings might be explained by the nature of the auditory information under investigation (i.e., vocal f_o and vocal SPL of speech sounds vs. pure tones) and differences in the tasks used (i.e., discrimination vs. magnitude estimation). PwPD have also been found to have a reduced sense of awareness of laryngeal somatosensory stimulation, with the severity of these deficits associated with the severity of auditory-perceptual measures of their vocal loudness and monotone quality (Hammer & Barlow, 2010).

Limb motor control literature in PwPD provides some insight as to how motor control is affected in PwPD. The striatal system is closely linked to motor learning, which suggests that deficits in striatal dopamine in PD can lead to degeneration of motor learning (Hikosaka, 1991, 1994; Redgrave et al., 2010). Motor learning deficits could limit the utility of clinical interventions in restoring movement (Frith et al., 1986; Nieuwboer et al., 2009; Wilkinson et al., 2009). However, findings on the ability of PwPD to learn and adapt to limb motor learning tasks have been inconsistent such that a subset observed motor learning capabilities in PwPD with reduced retention (Frith et al., 1986; Muslimovic et al., 2007; Pascual-Leone et al., 1993; Pendt et al., 2011; Roemmich et al., 2014) and another subset observed motor learning capabilities in PwPD that retained long term (Agostino et al., 1996; Behrman et al., 2000; Jessop et al., 2006; Jöbges et al., 2004; Klamroth et al., 2016; Protas et al., 2005; Shen & Mak, 2015; Smania et al., 2010; Smiley-Oyen et al., 2006). This could mean that only certain types of motor learning, such as implicit learning, are affected by the disease (see the work of Olson et al., 2019, for a review). In fact, recent studies have observed positive effects of motor learning–based physical therapy involving limb perturbations in PwPD (Klamroth et al., 2016; Roemmich et al., 2014; Shen & Mak, 2015; Yitayeh & Teshome, 2016). In terms of feedback control, past literature reports exaggerated latencies for reflexive responses to mechanical perturbations in PwPD for upper limb motor control (Rothwell et al., 1983). There is also evidence to suggest that PwPD lose the ability to scale these reflexive responses with respect to the perturbation (Bloem et al., 1995). In summary, motor integration seems to be adversely affected in PD and the feedback control mechanisms are enhanced to compensate for it, which eventually lead to hyperactivity

Table 1. Summary of key findings from main papers discussed in this review article.

Focused clinical population	Type of AAF	Key paper	Speaker profile	Acoustic features tested	Key findings	Notes
Idiopathic Parkinson's disease (IPD)	Reflexive AAF paradigm	X. Chen et al., 2013	Native speakers of Cantonese	Vocal f_o	• Larger reflexive compensatory vocal responses • AAF perturbation magnitude was positively correlated with response magnitude • Heterogeneity in individual vocal responses of PwPD vocal variability was significantly correlated with magnitude of reflexive compensatory vocal responses in PwPD	Participants were OFF PD medication for 12 hr prior experimentation
		Kiran & Larson, 2001	Native speakers of American English	Vocal f_o	• No significant differences in reflexive vocal responses between controls and PwPD • Temporal difference in vocal responses (larger response latencies in PD) • Heterogeneity in individual vocal responses of PwPD	Participants were ON typical PD medication
		H. Liu et al., 2012	Native speakers of American English	Vocal f_o and vocal SPL	• Larger reflexive compensatory vocal responses • Heterogeneity in individual vocal responses of PwPD directional differences in response to vocal SPL AAF perturbation in the control group	Participants were OFF PD medication for 12 hr prior experimentation
		Mollaei et al., 2016	Native speakers of American English	Vocal f_o	• Larger reflexive compensatory vocal responses • AAF perturbation magnitude was negatively correlated with response magnitude • Heterogeneity in individual vocal responses of PwPD	Participants were OFF PD medication for 12 hr prior experimentation
		Mollaei et al., 2019	Native speakers of American English	Vocal f_o	• Larger reflexive compensatory vocal responses • Heterogeneity in individual vocal responses of PwPD	Participants were OFF PD medication for 12 hr prior experimentation
		Abur, Subaciute, Daliri, et al., 2021	Native speakers of American English	Vocal f_o	• No significant differences in reflexive compensatory vocal responses between controls and PwPD • Heterogeneity in individual vocal responses of PwPD	Participants were ON typical PD medication

(*table continues*)

Table 1. *(Continued).*

Focused clinical population	Type of AAF	Key paper	Speaker profile	Acoustic features tested	Key findings	Notes
	Adaptive AAF paradigm	Abur, Subaciute, Daliri, et al., 2021	Native speakers of American English	Vocal f_o	• Heterogeneity in individual vocal responses of PwPD	Participants were ON typical PD medication
		Abur, Lester-Smith, et al., 2018	Native speakers of American English	Vocal f_o	• Reduced adaptive compensatory responses in PwPD relative to controls • Heterogeneity in individual vocal responses of PwPD	Participants were ON typical PD medication
		Senthinathan et al., 2021	Native speakers of American English	Vocal SPL	• Reduced adaptive compensatory vocal response magnitudes in PwPD relative to controls • Adaptive compensatory response magnitude differences for different AAF perturbation directions in PD group • Reduced levels of adaptive compensatory responses in PwPD relative to controls for contextually relevant conditions such as having a conversation and speaking in the presence of background noise	Participants were ON typical PD medication
Cerebellar degeneration (CD)	Reflexive AAF paradigm	Hilger, 2020	Native speakers of American English	Vocal f_o	• Reflexive compensatory vocal response magnitudes were larger in individuals with CD relative to controls	
		Houde et al., 2019	Native speakers of American English	Vocal f_o	• Reflexive compensatory vocal response magnitudes were larger in individuals with CD relative to controls	
		W. Li et al., 2019	Native speakers of American English	Vocal f_o	• Reflexive compensatory vocal response magnitudes were larger in individuals with CD relative to controls	
Hyperfunctional voice disorders (HVDs)	Reflexive AAF paradigm	Abur, Subaciute, Kapsner-Smith, et al., 2021	Native speakers of American English	Vocal f_o	• No significant differences between reflexive compensatory responses profiles between individuals with HVDs relative to control speakers	
		Ziethe et al., 2019	Native speakers of German	Vocal f_o	• Individuals with HVDs showed reflexive compensatory responses with large magnitudes and lower latencies for sustained vowel stimuli	

(*table continues*)

Table 1. *(Continued).*

Focused clinical population	Type of AAF	Key paper	Speaker profile	Acoustic features tested	Key findings	Notes
HVDs	Adaptive AAF paradigm	Abur, Subaciute, Kapsner-Smith, et al., 2021	Native speakers of American English	Vocal f_o	• Reduced adaptive compensatory response magnitudes in individuals with HVDs relative to control speakers • Larger individual variability in vocal responses in individuals with HVDs relative to controls	
		Stepp et al., 2017	Native speakers of American English	Vocal f_o	• Reduced adaptive compensatory response magnitudes in individuals with HVDs relative to control speakers • Larger individual variability in vocal responses in individuals with HVDs relative to controls	
Unilateral vocal fold paralysis (UVFP)	Reflexive AAF paradigm	Naunheim et al., 2019	Native speakers of American English	Vocal f_o	• Reduced vocal reflexive compensatory responses observed in individuals with UVFP relative to controls	
Laryngeal dystonia (LD)	Reflexive AAF paradigm	Thomas et al., 2021	Native speakers of American English	Vocal f_o	• Larger vocal reflexive compensatory responses in individuals with adductor type LD compared to controls	

Note. AAF = altered auditory feedback; f_o = fundamental frequency; PD = Parkinson's disease; PwPD = persons with PD; SPL = sound pressure level.

in feedback control. However, due to the variabilities in prior research findings based on the type of motor learning tested and/or the reflexive perturbation carried out, these outcomes are not directly generalizable for vocal motor control in PD. Furthermore, voice production involves a combination of motor and nonmotor components; thus, the deficits in vocal motor control will depend not only on motor deficits but also on nonmotor impairments such as cognitive decline, sensory dysfunction, and dysautonomia (Rana et al., 2015).

Reflexive AAF Studies in PD

There have been six studies that have used reflexive AAF paradigms to study auditory feedback control of vocal f_o in PwPD, compared to control groups of typical speakers without PD (Abur, Subaciute, Daliri, et al., 2021; X. Chen et al., 2013; Kiran & Larson, 2001; H. Liu et al., 2012; Mollaei et al., 2016, 2019). Four of the six studies reported larger reflexive compensatory vocal response magnitudes in the PwPD compared to control speakers, but no temporal differences in the vocal responses (X. Chen et al., 2013; H. Liu et al., 2012; Mollaei et al., 2016, 2019). Thus far, only one study has studied vocal SPL control via reflexive paradigms in PwPD (H. Liu et al., 2012), finding hyperactivity similar to the vocal f_o studies in their auditory feedback responses for vocal SPL. However, two studies of auditory feedback control of vocal f_o showed different findings. Both Kiran and Larson (2001) and Abur, Subaciute, Daliri, et al. (2021) failed to find any significant differences between vocal response magnitudes between PwPD and control groups. The conflicting findings are likely to be due to differences in the medication status of the participants being examined. All studies that found significant differences in vocal response magnitudes between PwPD and controls examined PwPD who had been off their typical medications for 12 hr prior to the experiment (studies carried out OFF medication: X. Chen et al., 2013; H. Liu et al., 2012; Mollaei et al., 2016, 2019), whereas the studies that did not find vocal response magnitude differences between groups examined PwPD while on their typical medications (studies carried out ON medication: Abur, Subaciute, Daliri, et al., 2021; Kiran & Larson, 2001). To our knowledge, no study has yet evaluated the effects of medication status on vocal response magnitudes in the same cohort with PwPD.

Medication status seems to be a crucial factor to consider in future AAF studies in PwPD. However, it is important to thoroughly consider the broader goals and impact of such research. The majority of PwPD are on medication to relieve motor symptoms that otherwise cause difficulties in their daily activities (Schapira, 2007). Although being off medication would remove it as a confounding variable in efforts to understand the basic science of vocal motor control in PD, it may not truly be beneficial in identifying effective interventions for voice disorders associated with the disease given that voice symptoms are not strongly affected by dopaminergic treatment (Rascol et al., 2003). Studies of PwPD on medication could be more advantageous if the goal is to improve speech outcomes for individuals who are typically on medication. On the other hand, if the goals are to (a) understand the basic science and pathology behind voice problems in PwPD or (b) identify the specific effects of medication on vocal motor control, studying PwPD both on and off medication would be valuable.

Accumulating evidence from vocal f_o reflexive studies on speakers with typical speech suggests that mechanisms underlying sensorimotor control of vocal f_o production seem to be language specific. Tonal language speakers tend to respond to vocal f_o perturbations faster and with larger compensatory magnitudes than nontonal language speakers (S. H. Chen et al., 2007; H. Liu et al., 2010). Participants of all studies discussed were native English speakers with the exception of X. Chen et al. (2013), which consisted of Cantonese speakers with and without PD. Mollaei et al. (2016) found that PwPD produced enhanced reflexive compensatory responses, relative to a control group, and the largest increase in the gain (i.e., the magnitude of the compensation divided by the magnitude of the perturbation) of the compensatory response in the PD group was observed for the smallest vocal f_o perturbation magnitude. This increase in response gain observed for native English speakers with PD was in contrast to the X. Chen et al. (2013) study, which found that PwPD exhibited larger reflexive compensatory responses as the perturbation magnitude increased. This is an important finding for future clinical interventions as it shows that voice therapy may need to be tailored to the language of the speaker.

All studies noted heterogeneity in the vocal responses generated by PwPD, compared to controls. It is possible that the individual variability seen in PwPD may be associated with the range of severity associated deficits. However, Mollaei et al. (2016) failed to find any correlations between vocal f_o compensation and disease severity for PwPD. The lack of correlations could be due to the fact that most participants in the study were rated to be in mild stages in disease severity. Thus, further studies should be conducted recruiting PwPD in a diverse spectrum of disease severity to comprehensively examine the relationship between sensorimotor deficits and disease severity. Another reason for higher vocal variability in PD could be due to weakened feedforward control mechanisms. X. Chen et al. (2013) showed that vocal f_o variability was significantly correlated with the magnitude of the vocal compensation in PwPD, but not in control speakers. The results suggest that atypical sensory motor integration of

f_o control in PD may be caused by the increased weighting of the auditory feedback control resulting from a possible weakened feedforward control function.

Adaptive AAF Studies in PD

Two studies on vocal f_o and one study on vocal SPL have been conducted thus far using adaptive paradigms in PwPD and control speakers (vocal f_o: Abur, Lester-Smith, et al., 2018; Abur, Subaciute, Daliri, et al., 2021; vocal SPL: Senthinathan et al., 2021). All studies recruited native English speakers and tested them while on medication. Abur, Lester-Smith, et al. (2018) found that PwPD showed reduced compensations to adaptive vocal f_o perturbations relative to controls at a group level. However, the individual responses in PwPD were highly variable. The magnitude of the adaptive response was not significantly correlated with age, disease progression, vocal f_o perceptual discrimination capability, or their speech intelligibility. However, a follow-up study performed using similar methodology, in a larger cohort of participants, failed to identify significant differences in adaptive responses between PwPD and age-, sex-, and hearing-matched control participants (Abur, Subaciute, Daliri, et al., 2021). These conflicting results indicate that further studies are required to understand auditory–motor integration of vocal f_o in PwPD.

The single study using an adaptive paradigm to study vocal SPL found that PwPD produced reduced vocal response magnitudes to AAF compared to controls (Senthinathan et al., 2021). Moreover, the magnitude of the compensatory response was significantly less in the negative perturbation direction in the PD group. This directional difference can be attributed to the observation that a decrease in loudness may be less perceptible and, thus, less primed for regulation, than an increase in loudness (Larson et al., 2007). However, this directional response difference was only found in the control group in H. Liu et al. (2012) for reflexive vocal SPL perturbations. While the argument holds for typical auditory–motor system function, why this may occur to a greater degree in PwPD and why it was only observed in an adaptive paradigm for vocal SPL perturbations and not in a reflexive paradigm remain unanswered questions. Senthinathan et al. (2021) also found that PwPD produced significantly reduced compensation magnitudes compared to controls specifically in the context of having a conversation and also in the presence of background noise. These results are consistent with prior findings in individuals with hypophonia related to PD, in which an overall gain reduction for vocal SPL and a gradual decrease in signal-to-noise ratio was found in the presence of increased background noise (Adams et al., 2006; Ho et al., 1999) and could be due to the compounded attentional demands associated with a conversational task and their impact on vocal SPL regulation (Adams & Dykstra, 2009).

Summary

AAF studies have provided crucial insights into the effects of PD on vocal motor control. Hyperactive auditory feedback responses in PwPD who are off medication have been noted by multiple studies for vocal f_o and one study for vocal SPL. Reduced adaptive responses were also observed in several studies carried out with PwPD on medication (vocal f_o: Abur, Lester-Smith, et al., 2018, vocal SPL: Senthinathan et al., 2021). Overall, these studies suggest that PwPD may rely more on auditory feedback due to impaired feedforward motor control and/or impaired somatosensory feedback. Finally, the use of speech tasks with differing communication intent in AAF studies showcases the importance of examining communication and social considerations in auditory–motor integration in PD.

CD

The cerebellum is speculated to be involved in the control of motor actions via projections to the primary motor cortex (Brodal & Bjaalie, 1997; Glickstein, 1992), playing a role in movement coordination, sequencing, timing, motor programming, inverse modeling, and sensory prediction (Manto et al., 2012). However, its specific role in the control of speech remains to be elucidated. Lesion and functional neuroimaging studies have shown that cerebellum is a crucial part of the speech motor control network (Ackermann, 2008; Bohland & Guenther, 2006; Ghosh et al., 2008). Neuroimaging studies have observed increased cerebral activation in response to both auditory (Tourville et al., 2008) and somatosensory (Golfinopoulos et al., 2011) perturbations of the jaw. There is abundant evidence for cerebellar contributions to motor and cognitive aspects of speech production, which include phonatory and articulatory control and verbal working memory. Specifically, the cerebellum has been implicated in controlling the online sequencing of syllable production during overt speech (Ackermann, 2008; Bohland & Guenther, 2006; Ghosh et al., 2008; Riecker et al., 2005). The underlying mechanisms of the functional roles of cerebellum in the feedback and feedforward control of speech production are still a matter of debate.

Clinical evidence in populations with CD points to the important role of cerebellum to speech production. For nonspeech movements, individuals with CD show profound deficits in updating feedforward motor commands. Across a broad range of tasks involving reaching and locomotion, these individuals exhibit a marked impairment in adapting to consistent perturbations (Day et al., 1998; Kawato & Wolpert, 1998; Manto et al., 2012; Morton & Bastian, 2006; Wolpert et al., 1998). Although less studied, feedback motor control mechanisms appear to be relatively intact in this population (Morton & Bastian, 2006; Rost et al., 2005; Smith & Shadmehr, 2005). However, a recent perturbation study investigated both force field and visuomotor perturbations in a single cohort of individuals with CD and found that the impairments observed in feedforward control for the two different tasks within participants were independent (Morton & Bastian, 2006). Thus, it is difficult to generalize these results to vocal motor function. In the DIVA model (Guenther, 2016), the cerebellum is hypothesized to use feedback signals from auditory and somatosensory areas to update the feedforward control of speech production. Several studies exploring feedback vocal motor control have confirmed that feedback control is intact in individuals with CD (Hilger, 2020; Houde et al., 2019; W. Li et al., 2019). However, no studies have explored feedforward vocal motor control in individuals with CD so far. The lack of adaptive studies of vocal motor control in individuals with CD makes these findings difficult to interpret for feedforward control, but we can speculate that individuals with CD may have hyperactive reflexive compensatory responses and hypoactive adaptive compensatory responses in vocal motor control (Morton & Bastian, 2006).

Reflexive AAF Studies in CD

To date, three studies have been carried out to understand responses to vocal f_o reflexive AAF paradigms in individuals with CD (Hilger, 2020; Houde et al., 2019; W. Li et al., 2019). Despite methodological differences in these studies, including the stimuli used, number of participants, and the magnitude of the AAF, all three studies showed similar findings: Reflexive compensatory responses were larger in individuals with CD relative to control speakers. Taken together, the results indicate that CD is associated with hyperactive auditory feedback control during speaking. Although no studies using adaptation techniques to study feedforward vocal motor control have been carried out in CD, based on the one prior study that used AAF of the first vowel formant (Parrell et al., 2017), we can speculate that feedforward function may be impaired in vocal motor control in individuals with CD and thus causes greater reliance on feedback control system for individuals with CD. However, if the cerebellum is preferentially involved in processing somatosensory feedback, as some models of speech production suggest (Hickok, 2012), then cerebellar damage might favor a shift to a greater reliance on auditory feedback. Thus, it is currently unclear if the higher reliance on auditory feedback for vocal motor control is due to impaired feedforward function, impaired somatosensory feedback function, or a combination of both. Therefore, further studies focused on feedforward and somatosensory feedback vocal motor control in individuals with CD are necessary.

Summary

The current knowledge we have gained from AAF paradigms in individuals with CD suggests that there is a possible overreliance on auditory feedback control. This is similar to the behavior found in PwPD via AAF studies. Thus, there is a possibility that current therapies for PwPD, such as Lee Silverman Voice Treatment (LSVT), may also be effective for populations with CD (Baumann et al., 2018; de Swart et al., 2003; Fox et al., 2002; Kamińska et al., 2007). In fact, there have been case studies in individuals with ataxic dysarthria in which LSVT has shown a positive impact (Lowit et al., 2020; Sapir et al., 2003), although more comprehensive studies are needed.

HVDs

HVDs are conditions associated with *vocal hyperfunction* (i.e., excessive perilaryngeal musculoskeletal activity during phonation; Oates & Winkworth, 2008). HVDs include muscle tension dysphonia (MTD; voice disorders in the absence of structural dysfunction) and benign lesions in the vocal folds (i.e., phonotrauma that arises and persists due to hyperfunctional vocal behavior; e.g., vocal fold nodules and polyps). Studies using AAF have indicated that there is a possible auditory–motor phenotype for individuals with HVDs in which atypical vocal motor control is observed (Abur, Subaciute, Kapsner-Smith, et al., 2021; Stepp et al., 2017; Ziethe et al., 2019).

Reflexive AAF Studies in HVDs

The reflexive vocal f_o AAF paradigm has been used in two studies to examine if the auditory feedback error control capability of individuals with HVDs was atypical compared to control speakers (Abur, Subaciute, Kapsner-Smith, et al., 2021; Ziethe et al., 2019). Sustained vowel phonation and speech tasks were used in the work of Ziethe et al. (2019) to investigate vocal motor control in 22 participants with MTD and 61 control speakers. Participants with MTD showed differences in auditory feedback error correction (i.e., reflexive responses with lower latencies and larger magnitudes) for sustained vowel stimuli, but no significant differences from control speakers during speech tasks. These results suggested that individuals with MTD have hyperactive to vocal f_o auditory feedback responses. The authors speculated that the apparent higher reliance to auditory feedback might be due to possible disturbances in somatosensory feedback in MTD. Abur, Subaciute, Kapsner-Smith, et al. (2021) also examined reflexive responses in 62 individuals with HVDs and 62 age- and sex-matched control speakers without HVDs matched for singing experience during sustained vowels. However, no significant differences were found between the reflexive response profiles between individuals with HVDs and control speakers. The later study outcomes suggested that individuals with HVDs have typical vocal f_o auditory feedback error-correction capability. These conflicting results suggest that further research is needed to identify the effects of HVDs on auditory feedback control for vocal f_o.

The conflicting results in these reflexive AAF studies in HVDs could be due to many reasons. Firstly, the perturbation magnitudes used in the two studies were quite different (+700 cents vs. ±100 cents). In fact, the Ziethe et al.'s (2019) perturbation magnitude (i.e., +700 cents) was substantially larger compared to all other reflexive paradigms in vocal f_o reported in literature (i.e., 50–500 cents). Prior studies in speakers with typical speech have noted that there is a general tendency of reduced vocal responses when the perturbation magnitude increases and a tendency to have more following responses (i.e., responses in the direction of the perturbation; Franken et al., 2021; H. Liu & Larson, 2007; H. Liu, Meshman, et al., 2011). Thus, the vocal motor control system seems to be optimally suited to compensate for small perturbations and the system's sensitivity to AAF is reduced when the perturbation becomes more distinguishable. Secondly, there were substantial differences in the cohorts of these two studies. The MTD and control cohorts were not age and sex matched in the work of Ziethe et al. (2019). Prior research in typical speakers has shown that age and sex affect the magnitude of reflexive f_o responses (Z. Chen et al., 2010; J. Li et al., 2018; P. Liu, Chen, et al., 2011) and the function of the auditory system is also essential to these responses. Thus, it is crucial to involve age-, sex-, and hearing-matched control speakers in AAF studies to remove any effects of these external factors contributing to vocal f_o control. Thirdly, the consistency of perturbations may impact the suitability of reflexive AAF paradigms. All trials in the reflexive paradigm in the work of Ziethe et al. (2019) were perturbed versus one fourth of total trials in the work of Abur, Subaciute, Kapsner-Smith, et al. (2021), which could have contributed to differing outcomes. The objective of reflexive paradigms is to observe a participant's response to sudden and unpredictable perturbations of vocal f_o. Generally, two techniques are used to maintain the unpredictability of a reflexive paradigm. The first technique is to perturb only 25%–50% trials to avoid the predictability of the perturbation. The second technique is to randomize the onset time of the perturbation within a single trial. The fact that neither of these techniques were used in the work of Ziethe et al. (2019) causes concern as to whether there was an adaptation to the perturbation occurring over time for the participants.

Adaptive AAF Studies in HVDs

Stepp et al. (2017) provided the first evidence that some individuals with HVDs demonstrated potential signs of a motor speech disorder, observing deficits in auditory feedback processing. Auditory–motor control was disrupted in those with HVDs compared to control speakers, with inappropriate updating and maintaining of feedforward vocal control based on auditory feedback. Abur, Subaciute, Kapsner-Smith, et al. (2021) also examined vocal motor control of vocal f_o in a much larger group of individuals with HVDs and sex- and singing experience-matched control participants via sensorimotor adaptation paradigms. The results were congruent with Stepp et al.'s observations that individuals with HVDs have auditory–motor integration impairments. Additionally, the later study also found that individuals with HVDs may have worse auditory discrimination capabilities compared to control speakers. Interestingly, both studies also observed larger individual variability in the vocal responses of individuals with HVDs compared to control speakers.

Summary

Overall, AAF studies have provided evidence that individuals with HVDs may have difficulty using auditory feedback to update their feedforward control subsystem. However, the conflicting results on feedback motor control in individuals with HVDs suggest that there should be more comprehensive investigations in the future with larger numbers of properly matched control and HVD groups to determine whether auditory feedback control is indeed unaffected by vocal hyperfunction. Overall, the outcomes of these AAF studies suggest that there are possible vocal motor control impairments in this population that should be taken into consideration when devising voice therapy programs for individuals with HVDs. However, these studies also showcase the inherent difficulties in carrying out AAF studies in this population. Individuals with HVDs may be unable to sustain vowels for longer periods of time, and there may be difficulty tracking vocal f_o in individuals with severely rough voice quality and/or diplophonia. It is crucial to keep these limitations in mind when designing future studies.

Vocal Fold Paralysis

Unilateral vocal fold paralysis (UVFP) is a clinical condition classically viewed as an isolated peripheral motor condition. A single study has been performed to evaluate whether UVFP is accompanied by central vocal motor control impairment, using reflexive vocal f_o AAF. Naunheim et al. (2019) studied nine UVFP patients treated by Type I thyroplasty with stable voices and compared their vocal responses to 12 control participants using a reflexive vocal f_o AAF paradigm. Individuals with UVFP had reduced reflexive compensatory responses compared to controls. The authors argue that this outcome suggests that isolated peripheral injury to the larynx may adversely impact central auditory processing, which in turn could contribute to a vocal motor impairment.

However, this interpretation should be taken with caution based on certain limitations in this initial study. Firstly, all trials of the reflexive paradigm were perturbed. Thus, there is a possible confound of the participants showing adaptive behavior to the perturbations in the later trials. Secondly, the control speakers were not sex matched to the individuals with UVFP (i.e., the majority of participants in UVFP group were female, and the majority of participants in control group were male). Unfortunately, sex is an external factor affecting vocal f_o control that could contribute to the vocal f_o response variability. Compared to female speakers, male speakers have been observed to produce significantly larger vocal f_o responses (Z. Chen et al., 2010). Thus, we expect a mismatch between groups could cause larger vocal f_o response magnitudes in the control group (i.e., the group with a male majority) compared to individuals with UVFP, regardless of any UVFP-specific characteristics. Thus, there is not sufficient evidence to conclude whether the group difference in this study is due to a sex mismatch or due to an underlying impairment in vocal motor control in individuals with UVFP. These interesting findings need to be explored in future, more comprehensive studies, particularly focusing on longitudinal changes in vocal motor control in individuals with UVFP. Outcomes of this type of work will enable better insight to for targeted therapy approaches for individuals with UVFP postsurgery.

LD

LD, also known as spasmodic dysphonia, is a rare voice disorder characterized by irregular voice breaks, due to involuntary contractions of the intrinsic laryngeal muscles. The pathophysiology of LD is poorly understood, which hampers proper clinical treatment and therapy for the disorders. However, several leading theories suggest that laryngeal somatosensory feedback function may be altered in LD patients (Ali et al., 2006; Ambalavanar et al., 2004; Aviv et al., 1999; Bhabu et al., 2003; Haslinger et al., 2005; Simonyan & Ludlow, 2010).

A single reflexive vocal f_o AAF study has been conducted in individuals with LD and control speakers to investigate auditory feedback control in individuals with LD. Thomas et al. (2021) tested 21 individuals with adductor type LD (ADLD) on the day of their presentation for botulinum toxin therapy and 11 control speakers. Individuals with ADLD produced significantly larger reflexive compensatory responses to the vocal f_o perturbation compared to the control speakers. This hyperactivity in auditory feedback could be interpreted as higher reliance on auditory feedback due to the potential deficit in the somatosensory feedback control, consistent with current theories about the pathophysiology of ADLD. If overreliance on auditory feedback was a compensatory mechanism in ADLD, one might expect it to be more pronounced in individuals with more severe vocal symptoms. However, the opposite was observed in the study. The magnitude of the vocal responses was negatively correlated with participants' responses to the Vocal Handicap Index (Jacobson et al., 1997) such that the individuals with ADLD who subjectively viewed themselves as highly symptomatic had the smallest responses to the vocal f_o reflexive paradigm. However, this observation could be due to a limitation of the study: Individuals with ADLD with severe voice breaks (six of the 21 speakers with ADLD) were eliminated from data analysis due to their inability to sustain vowels.

These results must be interpreted with caution as there are several limitations to this early study. These limitations need to be addressed in future studies of AAF in individuals with ADLD. Firstly, in the reflexive paradigm, 70%–80% of the trials were perturbed, suggesting that the unpredictable nature of the reflexive AAF paradigm was compromised, and thus, there may have been possible adaptation to the perturbations. Secondly, the individuals with ADLD were not sex matched with the control speakers (i.e., the majority of participants in ADLD group were female, and the majority of participants in the control group were male). Thus, there could be a possibility that sex-related variabilities in vocal motor control are also embedded in the vocal response variations found across the groups. As male participants have been observed to generate larger vocal f_o responses based on prior studies (Z. Chen et al., 2010), we would expect the sex-related variation to cause the vocal responses of the control speakers (i.e., the group with a male majority) to be larger than in individuals with ADLD. However, interestingly, the individuals with ADLD were observed to larger vocal f_o response magnitudes in the study. This may further bolster this finding in this case. Nevertheless, further experiments that address these limitations and in larger cohorts of participants with both adductor type and abductor type LD are necessary to elucidate the underlying vocal motor control mechanisms that are impacted in LD.

Clinical Implications

In this review article, we reviewed recent AAF studies carried out in individuals with voice disorders to understand the underlying mechanisms of their vocal motor control. The outcomes of these studies provide critical evidence as to how AAF studies can be improved for future studies to provide further insight about vocal motor control function. Although there have been many recent advancements in using AAF to study vocal motor control, much more is needed before this technique is ready for clinical translation.

How Can AAF Be Translated to the Clinic?

AAF paradigms have the potential to be used as investigative techniques to assess individuals with voice disorders with the objective of identifying the best behavioral treatment techniques for them. Additionally, AAF techniques show promise in being used in clinical environments to aid clinical diagnosis and intervention and as a measure of treatment efficacy. However, translating AAF techniques from specialized research settings to clinical environments includes many challenges. Nevertheless, it is crucial to improve AAF paradigms and understand the findings that result from them to pave the way to this transition.

There are multiple factors to consider relating to the use of AAF techniques in clinical environments. Currently, research facilities carrying out AAF experiments typically must have access to specialized equipment including soundproof rooms, high-end microphones and headphones, auditory feedback perturbation hardware/software, and specialized calibration equipment. This is a substantial barrier preventing the transition of AAF studies from research labs to clinical environments. More research is necessary to transition AAF paradigms into ecologically feasible formats. In order to shift from specialized hardware pitch shifters to more clinically friendly and portable options, the validity of software-based, user-friendly frequency shifting plugins for AAF should be carried out. Consideration should be given to exploring the implications of carrying out AAF paradigms in high ambient noise conditions. For example, research can focus on the feasibility of extracting vocal responses from neck accelerometer signals, which have been shown to be less affected by ambient noise compared to microphone signals in capturing speech acoustics (Coleman, 1988; Svec et al., 2005).

Multiple AAF studies investigating vocal motor control mechanisms in individuals with voice disorders have shown promising observations about the clinical utility of AAF as a diagnosis and assessment technique for voice disorders. AAF studies carried out in individuals with HVDs have shown that there is an inherent heterogeneity in these populations and there is a subset of individuals who present with auditory processing issues. AAF techniques may be a critical assessment method to identify this auditory–motor subtype, in order to generate specialized treatment strategies addressing the auditory deficits. Further research should be carried out in larger cohorts to define typical auditory–motor function (i.e., the range of typical vocal responses for adaptive and reflexive AAF paradigms in common voice parameters such as vocal f_o and vocal SPL), and these normative data sets can be used to characterize atypical auditory–motor function in clinical populations. The work of Abur, Subaciute, Kapsner-Smith, et al. (2021) is one such AAF study that characterized a large cohort of individuals with HVDs and control speakers in both singing and nonsinging populations. However, more research by independent groups needs to be conducted with these objectives. A recent study carried out in a large cohort of PwPD reported that there were no significant deficits in auditory–motor integration in PwPD compared to control group (Abur, Subaciute, Daliri, et al., 2021). The same study noted that individual productions were highly variable within participants, suggesting weak feedforward control mechanisms. If the auditory motor integration capabilities are intact in this population as observed, AAF could be used as an effective method to update the weak feedforward motor plans of PwPD. In fact, gait and balance studies have successfully used motor learning to reduce impaired motor integration in PwPD using similar technologies in limb motor control (see PD section for details). For voice disorders that introduce hyperactivation of auditory feedback control mechanism, either as a compensatory strategy or as a motor control deficit, masking noise can be used to introduce more variability in the auditory feedback system. The increased variability in auditory feedback may compel the speakers to rely on feedforward motor control and somatosensory feedback control for speech production, thus reducing the adverse effects of hyperactive feedback control.

How Can We Reduce Variability in AAF Experimental Methods?

In discussing the use and validity of AAF in measuring vocal motor control, it is necessary to come to a consensus about the protocols of reflexive and adaptive paradigms. Currently, there is heterogeneity in the experimental methods as described in the literature, with differing parameters including magnitude and direction of perturbation, number of trials perturbed, total number of trials, and overall design of the paradigm. This leaves much room for variation in responses and inconsistent results that cannot be compared across studies. Thus, there should be consensus among researchers using AAF paradigms about different parameters. We recommend that randomization of perturbed trials be required in addition to keeping consecutive perturbed trials at a minimum (i.e., less than five consecutive trials with 50% total trials being perturbed) in reflexive paradigms. This ensures that the AAF is unpredictable and that feedback error-based adaptation is avoided. As for adaptive paradigms, it is important to have a sufficient number of trials to elicit an adaptation effect, but not so many as to become exhaustive. For both reflexive and adaptive paradigms, it may also be worth integrating more ecologically valid stimuli, relative to current stimuli that are unnaturally long in duration. Because typical reflexive responses initiate between 100 and 120 ms after a perturbation and plateau at about 250 ms (Larson et al., 2001), a stimulus of 1 s (about a third of the duration of some paradigms in studies discussed in this review article) would be sufficient to capture vocal responses. Additionally, instead of sustained vowels, more naturalistic stimuli such as words with clear communicative context should be used for reflexive and adaptive AAF paradigms (Mollaei et al., 2016, 2019).

Apart from methodological differences, another crucial factor contributing to variability across different research studies are the individual source variations in voice production. These individual variabilities could be due to differences in vocal fold physiology due to an individual's sex (i.e., females have higher vocal f_o relative to males) and/or age (i.e., muscle atrophy causing vocal f_o to differ; Kaneko et al., 2015; Martins et al., 2015; Takano et al., 2010), an individual's singing experience (i.e., better vocal f_o control; Fulton, 2007), and/or voice usage. In addition to these demographic variations, individuals with specific voice disorders may have inherently atypical voice qualities (i.e., breathy, hoarse voice quality) affecting the validity of acoustic metric tracking in AAF paradigm data analysis. For example, vocal f_o mistracking due to voice aperiodicity, inability to sustain vowels, breathiness, and/or strain in individuals with HVDs is responsible for the majority of unusable data in studies in individuals with HVDs (Abur, Subaciute, Kapsner-Smith, et al., 2021; Stepp et al., 2017; Ziethe et al., 2019). Similarly, whispered or soft productions, vocal fry, breathiness, and/or the inability to sustain vowels is a major factor of vocal f_o mistracking in AAF studies in PwPD (Abur, Lester-Smith, et al., 2018; Abur, Subaciute, Daliri, et al., 2021; X. Chen et al., 2013; Kiran & Larson, 2001; H. Liu et al., 2012; Mollaei et al., 2013, 2016, 2019; Senthinathan et al., 2021). It is crucial to consider these factors when formulating AAF studies in different cohorts with voice disorders such that these factors are counterbalanced and matched across groups.

Comprehensive Investigation of Feedback and Feedforward Control in Single Cohorts

Most studies using AAF paradigms typically choose to use either a reflexive or an adaptive design to study either auditory feedback or feedforward control. However, conducting both paradigms in a single study can provide insight over overall vocal motor control (Abur, Subaciute, Daliri, et al., 2021). This can be valuable in understanding vocal motor control on an individual level as evidence from prior research suggests that individuals may have a preference of sensory feedback (i.e., auditory over somatosensory or vice versa; Lametti et al., 2012). These preferences may contribute to the differences in responses resulting from probing the feedback and feedforward control systems in the same individual. Information from the individual level is critical when attempting to make conclusions on a group level and thus should be studied more thoroughly through the incorporation of both reflexive and adaptive paradigms in a single study.

Conclusions

AAF studies in individuals with voice disorders have provided crucial insights on their underlying pathophysiology. Individuals with PD, CD, and ADLD all may have hypersensitivity in auditory feedback control. In PwPD, the hyperactivity seems to be a compensatory mechanism for an atypically weak feedforward control system. In individuals with CD and LD, the reasons for hyperactivity in auditory feedback remain to be investigated. In contrast, individuals with HVDs may have auditory–motor integration deficits, suggesting atypical ability to update feedforward control. Even in populations in which only peripheral vocal motor control is expected to be affected (e.g., UVFP), there may be compensatory issues with central vocal motor control that could be addressed in treatment. These findings may provide insight to clinicians in selecting effective treatment options for populations and one day for individuals, with voice disorders. For instance, treatments that are highly effective to one population with hyperactive auditory feedback function may be a potential intervention technique for other clinical populations with similar hyperactivity in auditory feedback. LSVT LOUD has shown success in PwPD and thus may show promise for individuals with CD and ADLD. Future collaboration between clinicians and researchers with the shared objective of improving AAF as an ecologically feasible and valid tool for clinical assessment may provide more personalized therapy targets for individuals with voice disorders.

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References

Abur, D., Lester-Smith, R. A., Daliri, A., Lupiani, A. A., Guenther, F. H., & Stepp, C. E. (2018). Sensorimotor adaptation of voice fundamental frequency in Parkinson's disease. *PLOS ONE, 13*(1), e0191839. https://doi.org/10.1371/journal.pone.0191839

Abur, D., Lupiani, A. A., Hickox, A. E., Shinn-Cunningham, B. G., & Stepp, C. E. (2018). Loudness perception of pure tones in Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 61*(6), 1487–1496. https://doi.org/10.1044/2018_JSLHR-H-17-0382

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

Abur, D., Subaciute, A., Kapsner-Smith, M., Segina, R. K., Tracy, L. F., Noordzij, J. P., & Stepp, C. E. (2021). Impaired auditory discrimination and auditory–motor integration in hyperfunctional voice disorders. *Scientific Reports, 11*(1), 13123. https://doi.org/10.1038/s41598-021-92250-8

Ackermann, H. (2008). Cerebellar contributions to speech production and speech perception: Psycholinguistic and neurobiological perspectives. *Trends in Neurosciences, 31*(6), 265–272. https://doi.org/10.1016/j.tins.2008.02.011

Adams, S., & Dykstra, A. (2009). Hypokinetic dysarthria. *Clinical Management of Sensorimotor Speech Disorders, 2*.

Adams, S., Dykstra, A., Abrams, K., Winnell, J., Jenkins, M., & Jog, M. (2006). Conversational speech intensity under different noise conditions in hypophonia and Parkinson's disease. *Canadian Acoustics, 34*(3), 96–97.

Agostino, R., Sanes, J. N., & Hallett, M. (1996). Motor skill learning in Parkinson's disease. *Journal of the Neurological Sciences, 139*(2), 218–226. https://doi.org/10.1016/0022-510X(96)00060-3

Ali, S. O., Thomassen, M., Schulz, G. M., Hosey, L. A., Varga, M., Ludlow, C. L., & Braun, A. R. (2006). Alterations in CNS activity induced by botulinum toxin treatment in spasmodic dysphonia: An H215O PET study. *Journal of Speech, Language, and Hearing Research, 49*(5), 1127–1146. https://doi.org/10.1044/1092-4388(2006/081)

Ambalavanar, R., Tanaka, Y., Selbie, W. S., & Ludlow, C. L. (2004). Neuronal activation in the medulla oblongata during selective elicitation of the laryngeal adductor response. *Journal of Neurophysiology, 92*(5), 2920–2932. https://doi.org/10.1152/jn.00064.2004

American Speech-Language-Hearing Association. (n.d.). *Voice disorders (Practice portal)*. Retrieved 12/03/2021 from https://www.asha.org/Practice-Portal/Clinical-Topics/Voice-Disorders/

Aviv, J. E., Martin, J. H., Kim, T., Sacco, R. L., Thomson, J. E., Diamond, B., & Close, L. G. (1999). Laryngopharyngeal sensory discrimination testing and the laryngeal adductor reflex. *Annals of Otology, Rhinology & Laryngology, 108*(8), 725–730. https://doi.org/10.1177/000348949910800802

Bauer, J. J., & Larson, C. R. (2003). Audio-vocal responses to repetitive pitch-shift stimulation during a sustained vocalization: Improvements in methodology for the pitch-shifting technique. *The Journal of the Acoustical Society of America, 114*(2), 1048–1054. https://doi.org/10.1121/1.1592161

Bauer, J. J., Mittal, J., Larson, C. R., & Hain, T. C. (2006). Vocal responses to unanticipated perturbations in voice loudness feedback: An automatic mechanism for stabilizing voice amplitude. *The Journal of the Acoustical Society of America, 119*(4), 2363–2371. https://doi.org/10.1121/1.2173513

Baumann, A., Nebel, A., Granert, O., Giehl, K., Wolff, S., Schmidt, W., Baasch, C., Schmidt, G., Witt, K., Deuschl, G., Hartwigsen, G., Zeuner, K. E., & van Eimeren, T. (2018). Neural correlates of hypokinetic dysarthria and mechanisms of effective voice treatment in Parkinson disease. *Neurorehabilitation and Neural Repair, 32*(12), 1055–1066. https://doi.org/10.1177/1545968318812726

Behrman, A. L., Cauraugh, J. H., & Light, K. E. (2000). Practice as an intervention to improve speeded motor performance and motor learning in Parkinson's disease. *Journal of the Neurological Sciences, 174*(2), 127–136. https://doi.org/10.1016/s0022-510x(00)00267-7

Behroozmand, R., & Sangtian, S. (2018). Neural bases of sensorimotor adaptation in the vocal motor system. *Experimental Brain Research, 236*(7), 1881–1895. https://doi.org/10.1007/s00221-018-5272-9

Bhabu, P., Poletto, C., Mann, E., Bielamowicz, S., & Ludlow, C. L. (2003). Thyroarytenoid muscle responses to air pressure stimulation of the laryngeal mucosa in humans. *Annals of Otology, Rhinology & Laryngology, 112*(10), 834–840. https://doi.org/10.1177/000348940311201002

Bloem, B. R., Beckley, D. J., Remler, M. P., Roos, R. A. C., & van Dijk, J. G. (1995). Postural reflexes in Parkinson's disease during 'resist' and 'yield' tasks. *Journal of the Neurological Sciences, 129*(2), 109–119. https://doi.org/10.1016/0022-510x(94)00253-k

Bohland, J. W., & Guenther, F. H. (2006). An fMRI investigation of syllable sequence production. *NeuroImage, 32*(2), 821–841. https://doi.org/10.1016/j.neuroimage.2006.04.173

Boone, D. R., McFarlane, S. C., Von Berg, S. L., & Zraick, R. I. (2005). *The voice and voice therapy*. Pearson/Allyn & Bacon.

Brodal, P., & Bjaalie, J. G. (1997). Chapter 13 salient anatomic features of the cortico-ponto-cerebellar pathway. *Progress in Brain Research, 114,* 227–249. https://doi.org/10.1016/s0079-6123(08)63367-1

Burnett, T. A., Freedland, M. B., Larson, C. R., & Hain, T. C. (1998). Voice F0 responses to manipulations in pitch feedback. *The Journal of the Acoustical Society of America, 103*(6), 3153–3161. https://doi.org/10.1121/1.423073

Burnett, T. A., Senner, J. E., & Larson, C. R. (1997). Voice F0 responses to pitch-shifted auditory feedback: A preliminary study. *Journal of Voice, 11*(2), 202–211. https://doi.org/10.1016/s0892-1997(97)80079-3

Chen, S. H., Liu, H., Xu, Y., & Larson, C. R. (2007). Voice F0 responses to pitch-shifted voice feedback during English speech. *The Journal of the Acoustical Society of America, 121*(2), 1157–1163. https://doi.org/10.1121/1.2404624

Chen, X., Zhu, X., Wang, E. Q., Chen, L., Li, W., Chen, Z., & Liu, H. (2013). Sensorimotor control of vocal pitch production in Parkinson's disease. *Brain Research, 1527,* 99–107. https://doi.org/10.1016/j.brainres.2013.06.030

Chen, Z., Liu, P., Jones, J. A., Huang, D., & Liu, H. (2010). Sex-related differences in vocal responses to pitch feedback perturbations during sustained vocalization. *The Journal of the Acoustical Society of America, 128*(6), EL355–EL360. https://doi.org/10.1121/1.3509124

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

Cohen, S. M., Kim, J., Roy, N., Asche, C., & Courey, M. (2012). Prevalence and causes of dysphonia in a large treatment-seeking population. *The Laryngoscope, 122*(2), 343–348. https://doi.org/10.1002/lary.22426

Coleman, R. F. (1988). Comparison of microphone and neck-mounted accelerometer monitoring of the performing voice. *Journal of Voice, 2*(3), 200–205. https://doi.org/10.1016/s0892-1997(88)80077-8

Critchley, E. M. (1981). Speech disorders of Parkinsonism: A review. *Journal of Neurology, Neurosurgery, & Psychiatry, 44*(9), 751–758. https://doi.org/10.1136/jnnp.44.9.751

Dastolfo-Hromack, C., & Walsh, E. (2020). Evaluation of neurogenic voice disorders. *Neurologic and Neurodegenerative Diseases of the Larynx, 53*. https://doi.org/10.1007/978-3-030-28852-5_5

Day, B. L., Thompson, P. D., Harding, A. E., & Marsden, C. D. (1998). Influence of vision on upper limb reaching movements in patients with cerebellar ataxia. *Brain, 121*(2), 357–372. https://doi.org/10.1093/brain/121.2.357

de Swart, B. J. M., Willemse, S. C., Maassen, B. A. M., & Horstink, M. W. I. M. (2003). Improvement of voicing in patients with Parkinson's disease by speech therapy. *Neurology, 60*(3), 498–500. https://doi.org/10.1212/01.wnl.0000044480.95458.56

Dorsey, E. R., Sherer, T., Okun, M. S., & Bloem, B. R. (2018). The emerging evidence of the Parkinson pandemic. *Journal of Parkinson's Disease, 8*(Suppl. 1), S3–S8. https://doi.org/10.3233/JPD-181474

Dromey, C., & Adams, S. (2000). Loudness perception and hypophonia in Parkinson disease. *Journal of Medical Speech-Language Pathology, 8*(4), 255–259.

Egan, J. J. (1975). Use of the Lombard response in cases of hysterical aphonia. *Archives of Otolaryngology, 101*(9), 557. https://doi.org/10.1001/archotol.1975.00780380035008

Elman, J. L. (1981). Effects of frequency-shifted feedback on the pitch of vocal productions. *The Journal of the Acoustical Society of America, 70*(1), 45–50. https://doi.org/10.1121/1.386580

Fox, C. M., Morrison, C. E., Ramig, L. O., & Sapir, S. (2002). Current perspectives on the Lee Silverman Voice Treatment (LSVT) for individuals with idiopathic Parkinson disease. *American Journal of Speech-Language Pathology, 11*(2), 111–123. https://doi.org/10.1044/1058-0360(2002/012)

Franken, M. K., Hartsuiker, R. J., Johansson, P., Hall, L., & Lind, A. (2021). Speaking with an alien voice: Flexible sense of agency during vocal production. *Journal of Experimental Psychology. Human Perception and Performance, 47*(4), 479–494. https://doi.org/10.1037/xhp0000799

Frith, C. D., Bloxham, C. A., & Carpenter, K. N. (1986). Impairments in the learning and performance of a new manual skill in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery, & Psychiatry, 49*(6), 661–668. https://doi.org/10.1136/jnnp.49.6.661

Fulton, K. S. (2007). *Vocal efficiency in trained singers vs. non-singers*. Brigham Young University.

Ghosh, S. S., Tourville, J. A., & Guenther, F. H. (2008). A neuroimaging study of premotor lateralization and cerebellar involvement in the production of phonemes and syllables. *Journal of Speech, Language, and Hearing Research, 51*(5), 1183–1202. https://doi.org/10.1044/1092-4388(2008/07-0119)

Glickstein, M. (1992). The cerebellum and motor learning. *Current Opinion in Neurobiology, 2*(6), 802–806. https://doi.org/10.1016/0959-4388(92)90137-a

Golfinopoulos, E., Tourville, J. A., Bohland, J. W., Ghosh, S. S., Nieto-Castanon, A., & Guenther, F. H. (2011). fMRI investigation of unexpected somatosensory feedback perturbation during speech. *NeuroImage, 55*(3), 1324–1338. https://doi.org/10.1016/j.neuroimage.2010.12.065

Grillo, E. U., Verdolini Abbott, K., & Lee, T. D. (2010). Effects of masking noise on laryngeal resistance for breathy, normal, and pressed voice. *Journal of Speech, Language, and Hearing Research, 53*(4), 850–861. https://doi.org/10.1044/1092-4388(2009/08-0069)

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

Hammer, M. J., & Barlow, S. M. (2010). Laryngeal somatosensory deficits in Parkinson's disease: Implications for speech respiratory and phonatory control. *Experimental Brain Research, 201*(3), 401–409. https://doi.org/10.1007/s00221-009-2048-2

Haslinger, B., Erhard, P., Dresel, C., Castrop, F., Roettinger, M., & Ceballos-Baumann, A. O. (2005). "Silent event-related" fMRI reveals reduced sensorimotor activation in laryngeal dystonia. *Neurology, 65*(10), 1562–1569. https://doi.org/10.1212/01.wnl.0000184478.59063.db

Hawco, C. S., & Jones, J. A. (2010). Multiple instances of vocal sensorimotor adaptation to frequency-altered feedback within a single experimental session. *The Journal of the Acoustical Society of America, 127*(1), EL13–EL18. https://doi.org/10.1121/1.3272633

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews. Neuroscience, 13*(2), 135–145. https://doi.org/10.1038/nrn3158

Hikosaka, O. (1991). Basal ganglia—Possible role in motor coordination and learning. *Current Opinion in Neurobiology, 1*(4), 638–643. https://doi.org/10.1016/s0959-4388(05)80042-x

Hikosaka, O. (1994). Role of basal ganglia in control of innate movements, learned behavior and cognition—A hypothesis. In *The basal ganglia IV* (pp. 589–596). Springer. https://doi.org/10.1007/978-1-4613-0485-2_61

Hilger, A. I. (2020). *Impaired sensorimotor integration for prosodic production in ataxic dysarthria*. Northwestern University. https://www.proquest.com/docview/2421404027?pq-origsite=gscholar&fromopenview=true

Ho, A. K., Bradshaw, J. L., Iansek, R., & Alfredson, R. (1999). Speech volume regulation in Parkinson's disease: Effects of implicit cues and explicit instructions. *Neuropsychologia, 37*(13), 1453–1460. https://doi.org/10.1016/s0028-3932(99)00067-6

Houde, J. F., Gill, J. S., Agnew, Z., Kothare, H., Hickok, G., Parrell, B., Ivry, R. B., & Nagarajan, S. S. (2019). Abnormally increased vocal responses to pitch feedback perturbations in patients with cerebellar degeneration. *The Journal of the Acoustical Society of America, 145*(5), EL372–EL378. https://doi.org/10.1121/1.5100910

Huang, X., Chen, X., Yan, N., Jones, J. A., Wang, E. Q., Chen, L., Guo, Z., Li, W., Liu, P., & Liu, H. (2016). The impact of Parkinson's disease on the cortical mechanisms that support auditory–motor integration for voice control. *Human Brain Mapping, 37*(12), 4248–4261. https://doi.org/10.1002/hbm.23306

Jacobson, B. H., Johnson, A., Grywalski, C., Silbergleit, A., Jacobson, G., Benninger, M. S., & Newman, C. W. (1997). The Voice Handicap Index (VHI). *American Journal of Speech-Language Pathology, 6*(3), 66–70. https://doi.org/10.1044/1058-0360.0603.66

Jessop, R. T., Horowicz, C., & Dibble, L. E. (2006). Motor learning and Parkinson disease: Refinement of movement velocity and endpoint excursion in a limits of stability balance task. *Neurorehabilitation and Neural Repair, 20*(4), 459–467. https://doi.org/10.1177/1545968306287107

Jones, J. A., & Munhall, K. G. (2000). Perceptual calibration of F0 production: Evidence from feedback perturbation. *The Journal of the Acoustical Society of America, 108*(3), 1246–1251. https://doi.org/10.1121/1.1288414

Jones, J. A., & Munhall, K. G. (2002). The role of auditory feedback during phonation: Studies of Mandarin tone production. *Journal of Phonetics, 30*(3), 303–320. https://doi.org/10.1006/jpho.2001.0160

Jöbges, M., Heuschkel, G., Pretzel, C., Illhardt, C., Renner, C., & Hummelsheim, H. (2004). Repetitive training of compensatory steps: A therapeutic approach for postural instability in Parkinson's disease. *Journal of Neurology, Neurosurgery, & Psychiatry, 75*(12), 1682–1687. https://doi.org/10.1136/jnnp.2003.016550

Jurgens, U. (2009). The neural control of vocalization in mammals: A review. *Journal of Voice, 23*(1), 1–10. https://doi.org/10.1016/j.jvoice.2007.07.005

Kamińska, I., Zebryk-Stopa, A., Pruszewicz, A., Dziubalska-Kołaczyk, K., Połczyńska-Fiszer, M., Pietrala, D., & Przedpelska-Ober, E. (2007). The progress in the rehabilitation of dysarthria in Parkinson disease using LSVT (Lee Silverman Voice Treatment). *Otolaryngologia polska= The Polish otolaryngology, 61*(5), 713–718. https://doi.org/10.1016/s0030-6657(07)70511-5

Kaneko, M., Hirano, S., Tateya, I., Kishimoto, Y., Hiwatashi, N., Fujiu-Kurachi, M., & Ito, J. (2015). Multidimensional Analysis on the effect of vocal function exercises on aged vocal fold atrophy. *Journal of Voice, 29*(5), 638–644. https://doi.org/10.1016/j.jvoice.2014.10.017

Katseff, S., Houde, J., & Johnson, K. (2012). Partial compensation for altered auditory feedback: A tradeoff with somatosensory feedback. *Language and Speech, 55*(2), 295–308. https://doi.org/10.1177/0023830911417802

Kawato, M., & Wolpert, D. (1998). Internal models for motor control. *Novartis Foundation Symposium, 218,* 291–304. Discussion 304–297. https://doi.org/10.1002/9780470515563.ch16

Keough, D., & Jones, J. A. (2009). The sensitivity of auditory–motor representations to subtle changes in auditory feedback while singing. *The Journal of the Acoustical Society of America, 126*(2), 837–846. https://doi.org/10.1121/1.3158600

Kiran, S., & Larson, C. R. (2001). Effect of duration of pitch-shifted feedback on vocal responses in patients with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 44*(5), 975–987. https://doi.org/10.1044/1092-4388(2001/076)

Klamroth, S., Steib, S., Gaßner, H., Goßler, J., Winkler, J., Eskofier, B., Klucken, J., & Pfeifer, K. (2016). Immediate effects of perturbation treadmill training on gait and postural control in patients with Parkinson's disease. *Gait & Posture, 50,* 102–108. https://doi.org/10.1016/j.gaitpost.2016.08.020

Lametti, D. R., Nasir, S. M., & Ostry, D. J. (2012). Sensory preference in speech production revealed by simultaneous alteration of auditory and somatosensory feedback. *The Journal of Neuroscience, 32*(27), 9351–9358. https://doi.org/10.1523/JNEUROSCI.0404-12.2012

Lane, H., & Tranel, B. (1971). The Lombard sign and the role of hearing in speech. *Journal of Speech and Hearing Research, 14*(4), 677–709. https://doi.org/10.1044/jshr.1404.677

Larson, C. R., Burnett, T. A., Bauer, J. J., Kiran, S., & Hain, T. C. (2001). Comparison of voice F0 responses to pitch-shift onset and offset conditions. *The Journal of the Acoustical Society of America, 110*(6), 2845–2848. https://doi.org/10.1121/1.1417527

Larson, C. R., Sun, J., & Hain, T. C. (2007). Effects of simultaneous perturbations of voice pitch and loudness feedback on voice F0 and amplitude control. *The Journal of the Acoustical Society of America, 121*(5, Pt. 1), 2862–2872. https://doi.org/10.1121/1.2715657

Li, J., Hu, H., Chen, N., Jones, J. A., Wu, D., Liu, P., & Liu, H. (2018). Aging and sex influence cortical auditory–motor integration for speech control. *Frontiers in Neuroscience, 12,* 749. https://doi.org/10.3389/fnins.2018.00749

Li, W., Zhuang, J., Guo, Z., Jones, J. A., Xu, Z., & Liu, H. (2019). Cerebellar contribution to auditory feedback control of speech production: Evidence from patients with spinocerebellar ataxia. *Human Brain Mapping, 40*(16), 4748–4758. https://doi.org/10.1002/hbm.24734

Lim, S. Y., Fox, S. H., & Lang, A. E. (2009). Overview of the extranigral aspects of Parkinson disease. *Archives of Neurology, 66*(2), 167–172. https://doi.org/10.1001/archneurol.2008.561

Lincoln, M., Packman, A., & Onslow, M. (2006). Altered auditory feedback and the treatment of stuttering: A review. *Journal of Fluency Disorders, 31*(2), 71–89. https://doi.org/10.1016/j.jfludis.2006.04.001

Liu, H., & Larson, C. R. (2007). Effects of perturbation magnitude and voice F0 level on the pitch-shift reflex. *The Journal of the Acoustical Society of America, 122*(6), 3671–3677. https://doi.org/10.1121/1.2800254

Liu, H., Meshman, M., Behroozmand, R., & Larson, C. R. (2011). Differential effects of perturbation direction and magnitude on the neural processing of voice pitch feedback. *Clinical Neurophysiology, 122*(5), 951–957. https://doi.org/10.1016/j.clinph.2010.08.010

Liu, H., Wang, E. Q., Chen, Z., Liu, P., Larson, C. R., & Huang, D. (2010). Effect of tonal native language on voice fundamental frequency responses to pitch feedback perturbations during sustained vocalizations. *The Journal of the Acoustical Society of America, 128*(6), 3739–3746. https://doi.org/10.1121/1.3500675

Liu, H., Wang, E. Q., Metman, L. V., & Larson, C. R. (2012). Vocal responses to perturbations in voice auditory feedback in individuals with Parkinson's disease. *PLOS ONE, 7*(3), e33629. https://doi.org/10.1371/journal.pone.0033629

Liu, P., Chen, Z., Jones, J. A., Huang, D., & Liu, H. (2011). Auditory feedback control of vocal pitch during sustained vocalization: A cross-sectional study of adult aging. *PLOS ONE, 6*(7), e22791. https://doi.org/10.1371/journal.pone.0022791

Logemann, J. A., Fisher, H. B., Boshes, B., & Blonsky, E. R. (1978). Frequency and cooccurrence of vocal tract dysfunctions in the speech of a large sample of Parkinson patients. *Journal of Speech and Hearing Disorders, 43*(1), 47–57. https://doi.org/10.1044/jshd.4301.47

Lowit, A., Egan, A., & Hadjivassiliou, M. (2020). Feasibility and acceptability of Lee Silverman Voice Treatment in progressive ataxias. *Cerebellum, 19*(5), 701–714. https://doi.org/10.1007/s12311-020-01153-3

Ludlow, C. L. (2005). Central nervous system control of the laryngeal muscles in humans. *Respiratory Physiology & Neurobiology, 147*(2–3), 205–222. https://doi.org/10.1016/j.resp.2005.04.015

Manto, M., Bower, J. M., Conforto, A. B., Delgado-García, J. M., da Guarda, S. N. F., Gerwig, M., Habas, C., Hagura, N., Ivry, R. B., Mariën, P., Molinari, M., Naito, E., Nowak, D. A., Oulad Ben Taib, N., Pelisson, D., Tesche, C. D., Tilikete, C., & Timmann, D. (2012). Consensus paper: Roles of the cerebellum in motor control–the diversity of ideas on cerebellar involvement in movement. *The Cerebellum, 11*(2), 457–487. https://doi.org/10.1007/s12311-011-0331-9

Martins, R. H., Benito Pessin, A. B., Nassib, D. J., Branco, A., Rodrigues, S. A., & Matheus, S. M. (2015). Aging voice and the laryngeal muscle atrophy. *The Laryngoscope, 125*(11), 2518–2521. https://doi.org/10.1002/lary.25398

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., Baum, S. R., & Gracco, V. L. (2019). The relationship between speech perceptual discrimination and speech production in Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 62*(12), 4256–4268. https://doi.org/10.1044/2019_Jslhr-S-18-0425

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

Morton, S. M., & Bastian, A. J. (2006). Cerebellar contributions to locomotor adaptations during splitbelt treadmill walking. *The Journal of Neuroscience, 26*(36), 9107–9116. https://doi.org/10.1523/JNEUROSCI.2622-06.2006

Muslimovic, D., Post, B., Speelman, J. D., & Schmand, B. (2007). Motor procedural learning in Parkinson's disease. *Brain, 130*(11), 2887–2897. https://doi.org/10.1093/brain/awm211

Naunheim, M. L., Yung, K. C., Schneider, S. L., Henderson-Sabes, J., Kothare, H., Mizuiri, D., Klein, D. J., Houde, J. F., Nagarajan, S. S., & Cheung, S. W. (2019). Vocal motor control and central auditory impairments in unilateral vocal fold paralysis. *The Laryngoscope, 129*(9), 2112–2117. https://doi.org/10.1002/lary.27680

Nieuwboer, A., Rochester, L., Muncks, L., & Swinnen, S. P. (2009). Motor learning in Parkinson's disease: Limitations and potential for rehabilitation. *Parkinsonism & Related Disorders, 15*(Suppl. 3), S53–S58. https://doi.org/10.1016/S1353-8020(09)70781-3

Oates, J., & Winkworth, A. (2008). Current knowledge, controversies and future directions in hyperfunctional voice disorders. *International Journal of Speech-Language Pathology, 10*(4), 267–277. https://doi.org/10.1080/17549500802140153

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 in Neurology, 10,* 62. https://doi.org/10.3389/fneur.2019.00062

Parkinson, A. L., Flagmeier, S. G., Manes, J. L., Larson, C. R., Rogers, B., & Robin, D. A. (2012). Understanding the neural mechanisms involved in sensory control of voice production. *NeuroImage, 61*(1), 314–322. https://doi.org/10.1016/j.neuroimage.2012.02.068

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. *The Journal of Neuroscience, 37*(38), 9249–9258. https://doi.org/10.1523/JNEUROSCI.3363-16.2017

Pascual-Leone, A., Grafman, J., Clark, K., Stewart, M., Massaquoi, S., Lou, J. S., & Hallett, M. (1993). Procedural learning in Parkinson's disease and cerebellar degeneration. *Annals of Neurology, 34*(4), 594–602. https://doi.org/10.1002/ana.410340414

Pendt, L. K., Reuter, I., & Muller, H. (2011). Motor skill learning, retention, and control deficits in Parkinson's disease. *PLOS ONE, 6*(7), e21669. https://doi.org/10.1371/journal.pone.0021669

Postuma, R. B., Aarsland, D., Barone, P., Burn, D. J., Hawkes, C. H., Oertel, W., & Ziemssen, T. (2012). Identifying prodromal Parkinson's disease: Pre-motor disorders in Parkinson's disease. *Movement Disorders, 27*(5), 617–626. https://doi.org/10.1002/mds.24996

Protas, E. J., Mitchell, K., Williams, A., Qureshy, H., Caroline, K., & Lai, E. C. (2005). Gait and step training to reduce falls in Parkinson's disease. *NeuroRehabilitation, 20*(3), 183–190. https://doi.org/10.3233/NRE-2005-20305

Ramig, L. O., & Verdolini, K. (1998). Treatment efficacy: Voice disorders. *Journal of Speech, Language, and Hearing Research, 41*(1), S101–S116. https://doi.org/10.1044/jslhr.4101.s101

Rana, A. Q., Ahmed, U. S., Chaudry, Z. M., & Vasan, S. (2015). Parkinson's disease: A review of non-motor symptoms. *Expert Review of Neurotherapeutics, 15*(5), 549–562. https://doi.org/10.1586/14737175.2015.1038244

Rascol, O., Payoux, P., Ory, F., Ferreira, J. J., Brefel-Courbon, C., & Montastruc, J. L. (2003). Limitations of current Parkinson's disease therapy. *Annals of Neurology, 53*(Suppl. 3), S3–12. Discussion S12–15. https://doi.org/10.1002/ana.10513

Redgrave, P., Rodriguez, M., Smith, Y., Rodriguez-Oroz, M. C., Lehericy, S., Bergman, H., Agid, Y., DeLong, M. R., & Obeso, J. A. (2010). Goal-directed and habitual control in the basal ganglia: Implications for Parkinson's disease. *Nature Reviews. Neuroscience, 11*(11), 760–772. https://doi.org/10.1038/nrn2915

Richardson, K., Sussman, J. E., & Stathopoulos, E. T. (2014). The effect of increased vocal intensity on interarticulator timing in speakers with Parkinson's disease: A preliminary analysis. *Journal of Communication Disorders, 52,* 44–64. https://doi.org/10.1016/j.jcomdis.2014.09.004

Riecker, A., Mathiak, K., Wildgruber, D., Erb, M., Hertrich, I., Grodd, W., & Ackermann, H. (2005). fMRI reveals two distinct cerebral networks subserving speech motor control. *Neurology, 64*(4), 700–706. https://doi.org/10.1212/01.WNL.0000152156.90779.89

Roemmich, R. T., Nocera, J. R., Stegemoller, E. L., Hassan, A., Okun, M. S., & Hass, C. J. (2014). Locomotor adaptation and locomotor adaptive learning in Parkinson's disease and normal aging. *Clinical Neurophysiology, 125*(2), 313–319. https://doi.org/10.1016/j.clinph.2013.07.003

Rost, K., Nowak, D. A., Timmann, D., & Hermsdorfer, J. (2005). Preserved and impaired aspects of predictive grip force control in cerebellar patients. *Clinical Neurophysiology, 116*(6), 1405–1414. https://doi.org/10.1016/j.clinph.2005.02.015

Rothwell, J. C., Obeso, J. A., Traub, M. M., & Marsden, C. D. (1983). The behaviour of the long-latency stretch reflex in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery, & Psychiatry, 46*(1), 35–44. https://doi.org/10.1136/jnnp.46.1.35

Roy, N., Merrill, R. M., Gray, S. D., & Smith, E. M. (2005). Voice disorders in the general population: Prevalence, risk factors, and occupational impact. *The Laryngoscope, 115*(11), 1988–1995. https://doi.org/10.1097/01.mlg.0000179174.32345.41

Rubin, J. S., Sataloff, R. T., & Korovin, G. S. (2014). *Diagnosis and treatment of voice disorders*. Plural.

Sapir, S., Spielman, J., Ramig, L. O., Hinds, S. L., Countryman, S., Fox, C., & Story, B. (2003). Effects of intensive voice treatment (the Lee Silverman Voice Treatment [LSVT]) on ataxic dysarthria: A case study. *American Journal of Speech-Language Pathology, 12*(4), 387–399. https://doi.org/10.1044/1058-0360(2003/085)

Schapira, A. H. V. (2007). Treatment options in the modern management of Parkinson disease. *Archives of Neurology, 64*(8), 1083–1088. https://doi.org/10.1001/archneur.64.8.1083

Scheerer, N. E., Jacobson, D. S., & Jones, J. A. (2016). Sensorimotor learning in children and adults: Exposure to frequency-altered auditory feedback during speech production. *Neuroscience, 314,* 106–115. https://doi.org/10.1016/j.neuroscience.2015.11.037

Schenck, A., Hilger, A. I., Levant, S., Kim, J. H., Lester-Smith, R. A., & Larson, C. (2020). The effect of pitch and loudness auditory feedback perturbations on vocal quality during sustained phonation. *Journal of Voice*. https://doi.org/10.1016/j.jvoice.2020.11.001

Senthinathan, A., Adams, S., Page, A. D., & Jog, M. (2021). Speech intensity response to altered intensity feedback in individuals with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 64*(6S), 2261–2275. https://doi.org/10.1044/2021_JSLHR-20-00278

Shen, X., & Mak, M. K. Y. (2015). Technology-assisted balance and gait training reduces falls in patients with Parkinson's disease: A randomized controlled trial with 12-month follow-up. *Neurorehabilitation and Neural Repair, 29*(2), 103–111. https://doi.org/10.1177/1545968314537559

Simonyan, K., & Ludlow, C. L. (2010). Abnormal activation of the primary somatosensory cortex in spasmodic dysphonia: An fMRI study. *Cerebral Cortex, 20*(11), 2749–2759. https://doi.org/10.1093/cercor/bhq023

Smania, N., Corato, E., Tinazzi, M., Stanzani, C., Fiaschi, A., Girardi, P., & Gandolfi, M. (2010). Effect of balance training on postural instability in patients with idiopathic Parkinson's disease. *Neurorehabilitation and Neural Repair, 24*(9), 826–834. https://doi.org/10.1177/1545968310376057

Smiley-Oyen, A. L., Lowry, K. A., & Emerson, Q. R. (2006). Learning and retention of movement sequences in Parkinson's disease. *Movement Disorders, 21*(8), 1078–1087. https://doi.org/10.1002/mds.20906

Smith, M. A., & Shadmehr, R. (2005). Intact ability to learn internal models of arm dynamics in Huntington's disease but not cerebellar degeneration. *Journal of Neurophysiology, 93*(5), 2809–2821. https://doi.org/10.1152/jn.00943.2004

Stathopoulos, E. T., Huber, J. E., Richardson, K., Kamphaus, J., DeCicco, D., Darling, M., Fulcher, K., & Sussman, J. E. (2014). Increased vocal intensity due to the Lombard effect in speakers with Parkinson's disease: Simultaneous laryngeal and respiratory strategies. *Journal of Communication Disorders, 48,* 1–17. https://doi.org/10.1016/j.jcomdis.2013.12.001

Stemple, J. C., Roy, N., & Klaben, B. K. (2018). *Clinical voice pathology: Theory and management*. Plural.

Stepp, C. E., Lester-Smith, R. A., Abur, D., Daliri, A., Pieter Noordzij, J., & 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

Svec, J. G., Titze, I. R., & Popolo, P. S. (2005). Estimation of sound pressure levels of voiced speech from skin vibration of the neck. *The Journal of the Acoustical Society of America, 117*(3), 1386–1394. https://doi.org/10.1121/1.1850074

Takano, S., Kimura, M., Nito, T., Imagawa, H., Sakakibara, K., & Tayama, N. (2010). Clinical analysis of presbylarynx–vocal fold atrophy in elderly individuals. *Auris Nasus Larynx, 37*(4), 461–464. https://doi.org/10.1016/j.anl.2009.11.013

Thomas, A., Mirza, N., & Eliades, S. J. (2021). Auditory feedback control of vocal pitch in spasmodic dysphonia. *The Laryngoscope, 131*(9), 2070–2075. https://doi.org/10.1002/lary.29254

Titze, I. R. (2000). *Principles of voice production (second printing)*. National Center for Voice and Speech.

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

Troche, J., Troche, M. S., Berkowitz, R., Grossman, M., & Reilly, J. (2012). Tone discrimination as a window into acoustic perceptual deficits in Parkinson's disease. *American Journal of Speech-Language Pathology, 21*(3), 258–263. https://doi.org/10.1044/1058-0360(2012/11-0007)

Verdolini, K., Rosen, C. A., & Branski, R. C. (2014). *Classification manual for voice disorders-I*. Psychology Press. https://doi.org/10.4324/9781410617293

Wilkinson, L., Khan, Z., & Jahanshahi, M. (2009). The role of the basal ganglia and its cortical connections in sequence learning: Evidence from implicit and explicit sequence learning in Parkinson's disease. *Neuropsychologia, 47*(12), 2564–2573. https://doi.org/10.1016/j.neuropsychologia.2009.05.003

Willis, G. L., Moore, C., & Armstrong, S. M. (2012). Breaking away from dopamine deficiency: An essential new direction for Parkinson's disease. *Reviews in the Neurosciences, 23*(4), 403–428. https://doi.org/10.1515/revneuro-2012-0037

Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences, 2*(9), 338–347. https://doi.org/10.1016/s1364-6613(98)01221-2

Yitayeh, A., & Teshome, A. (2016). The effectiveness of physiotherapy treatment on balance dysfunction and postural instability in persons with Parkinson's disease: A systematic review and meta-analysis. *BMC Sports Science, Medicine and Rehabilitation, 8*(1), 17. https://doi.org/10.1186/s13102-016-0042-0

Zhang, Z. (2016). Mechanics of human voice production and control. *The Journal of the Acoustical Society of America, 140*(4), 2614–2635. https://doi.org/10.1121/1.4964509

Ziethe, A., Petermann, S., Hoppe, U., Greiner, N., Bruning, M., Bohr, C., & Dollinger, M. (2019). Control of fundamental frequency in dysphonic patients during phonation and speech. *Journal of Voice, 33*(6), 851–859. https://doi.org/10.1016/j.jvoice.2018.07.001

Zollinger, S. A., & Brumm, H. (2011). The Lombard effect. *Current Biology, 21*(16), R614–R615. https://doi.org/10.1016/j.cub.2011.06.003