Review Article

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

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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.

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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 expelled 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 vibratory 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 relies on 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 $f_0$ reflexive responses—Burnett et al., 1997, 1998, vocal SPL reflexive responses—Bauer et al., 2006; Larson et al., 2007, vocal $f_0$ 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
findings grouped by specific clinical population. See pathophysiology of voice disorders through the use of to provide perspective on what has been learned about the findings, similarities, and variations in these AAF studies. The goal of this review article is to provide a summary of the vocal fold paralysis, and laryngeal dystonia (LD). The degeneration (CD), hyperfunctional voice disorders (HVDs), voice disorders, including individuals with PD, cerebellar ease (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 $f_0$ 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
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| HVDs                        | Adaptive AAF paradigm | Abur, Subaciute, Kapsner-Smith, et al., 2021 | Native speakers of American English | Vocal $f_0$ | • 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 $f_0$ | • Reduced adaptive compensatory response magnitudes in individuals with HVDs relative to controls  
• 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 $f_0$ | • Reduced vocal reflexive compensatory responses observed in individuals with UVFP relative to controls  
• Larger vocal reflexive compensatory responses in individuals with adductor type LD compared to controls |       |
| Laryngeal dystonia (LD)     | Reflexive AAF paradigm | Thomas et al., 2021 | Native speakers of American English | Vocal $f_0$ | • Reduced vocal reflexive compensatory responses observed in individuals with UVFP relative to controls  
• Larger vocal reflexive compensatory responses in individuals with adductor type LD compared to controls |       |

Note. AAF = altered auditory feedback; $f_0$ = 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 $f_0$ 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 $f_0$ studies in their auditory feedback responses for vocal SPL. However, two studies of auditory feedback control of vocal $f_0$ 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 $f_0$ reflexive studies on speakers with typical speech suggests that mechanisms underlying sensorimotor control of vocal $f_0$ production seem to be language specific. Tonal language speakers tend to respond to vocal $f_0$ 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 $f_0$ 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 $f_0$ 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 $f_0$ 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
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 visuo-motor 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 diplonhonia. 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 $f_0$ control that could contribute to the vocal $f_0$ response variability. Compared to female speakers, male speakers have been observed to produce significantly larger vocal $f_0$ responses (Z. Chen et al., 2010). Thus, we expect a mismatch between groups could cause larger vocal $f_0$ 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 impacted in LD. The pathophysiology of LD is poorly understood, 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 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 $f_0$ and vocal SPL), and these normative data sets can be used to characterize atypical auditory–motor function in clinical populations. The work of Abur, Subacicate, 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, Subacicate, 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 f0 relative to males) and/or age (i.e., muscle atrophy causing vocal f0 to differ; Kaneko et al., 2015; Martins et al., 2015; Takano et al., 2010), an individual’s singing experience (i.e., better vocal f0 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 f0 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 f0 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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