Auditory-Motor Function Pre- and Post-Therapy in Hyperfunctional Voice Disorders: A Case Series

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Summary: Objective/Hypothesis. Behavioral voice therapy is the most common treatment for hyperfunctional voice disorders (HVDs) but has limited long-term effectiveness since the comprehensive mechanisms underlying HVDs remain unclear. Recent work has implicated disordered sensorimotor integration during speech in some speakers with HVDs and suggests that auditory processing is a key factor to consider in HVD assessment and therapy. The purpose of this case-series study was to assess whether current voice therapy approaches for HVDs resulted in improvements to auditory-motor function.

Study Design. Longitudinal (pre-post) study.

Method. Pre and postvoice therapy for HVDs, 11 speakers underwent an assessment of auditory-motor function via auditory discrimination of vocal pitch, responses to unanticipated auditory perturbations, and responses to predictable auditory perturbations of vocal pitch.

Results. At the post-therapy session, 10 out of 11 participants demonstrated voice therapy success (via self-reported voice problems and/or auditory-perceptual judgements of voice by a clinician) and eight of the 11 participants demonstrated improvements in at least one measure of auditory discrimination and/or auditory-motor control. Specifically, three speakers demonstrated improvements in auditory discrimination, five speakers demonstrated improved (within typical cutoffs) responses to predictable perturbations, and two speakers demonstrated improvements in both auditory discrimination and auditory-motor measures.

Conclusions. Together, these findings support that voice therapy in individuals with HVDs may impact auditory-motor control and highlight the potential benefit of systematically addressing auditory function in voice therapy and assessment for HVDs.

Key Words: Auditory-motor control–Hyperfunctional voice disorders–Vocal nodules–Voice therapy–Auditory processing–Auditory perturbations.

INTRODUCTION

Approximately 30% of individuals will develop a voice disorder across their lifespan and hyperfunctional voice disorders (HVDs) have been reported as the most common clinical diagnosis in voice clinics 45%. Thus, HVDs are highly prevalent and can result in substantial declines in quality of life, including worse job performance, disrupted communicative ability, and increased isolation due to avoidance of social activities. HVDs present with heterogenous symptoms, but they are typically associated with excessive peri-laryngeal muscle tension and improper muscle patterns. These inappropriate muscle patterns can occur with or without phonotraumatic lesions on the vocal folds. HVDs have been extensively examined over decades of research (reviewed below), but all the factors that contribute to the onset and persistence of symptoms have yet to be clearly identified.

There are no universal criteria for clinical diagnosis and management of HVDs, but several factors have been attributed to their development. Primarily, HVDs are linked to voice use and are frequently reported by individuals with high voice use professions e.g., singers and teachers. Some have also postulated that there are links between HVDs and psychosocial behavior and autonomic dysfunction. The combination of risk factors in HVDs and the unclear underlying mechanisms are an obstacle for diagnosis, assessment, and therapeutic approaches.

There are also subtypes of HVDs: phonotraumatic vocal hyperfunction (PVH), which includes lesions on the vocal folds, and non-phonotraumatic vocal hyperfunction (NPVH), which occurs in the absence of any lesions. For the latter, NPVH is often a diagnosis of exclusion i.e., individuals receive an HVD diagnosis if there are no other clear structural or neurological reasons for the voice changes.

Although HVDs are clearly associated with impaired voice production, recent findings suggest that atypical auditory function may also be an additional factor in their presentation. This possibility is theoretically motivated by notable similarities in speech subsystem disruptions between individuals with HVDs and individuals with hearing loss. In the respiratory subsystem, speakers with...
breathing that is also observed in HVDs. In the laryngeal subsystem, both speakers with HVDs and speakers with hearing loss have shown increased subglottal pressure during voicing compared to speakers with typical voices. Additionally, the voices of speakers with hearing loss are rated as perceptually breathy and strained, much like some speakers with HVDs. In the articulatory subsystem, speakers with hearing loss show restricted tongue movements during vowel production compared to typical speakers, which is in alignment with the reduced vowel space observed in HVDs.

The role of auditory processing deficits in HVD symptoms is supported by current models of speech motor control: the generation of appropriate laryngeal muscle control patterns depends on the ability to detect sensory (somatosensory and auditory) changes and generate corrective output. Specifically, auditory-motor control of voice requires (1) the detection of auditory errors (the mismatch between expected and actual feedback), (2) generation of a corrective motor plan by the auditory feedback system, and (3) updating of the feedforward system to incorporate the corrective plan into future utterances auditory-motor integration. Therefore, the persistent improper laryngeal control in individuals with HVDs may result from atypical auditory-motor function.

Auditory-motor control of voice can be examined experimentally with the use of pitch-shifting technology. The detection of auditory errors can be examined via comparisons of typical and pitch-shifted stimuli in a listening task to determine listeners’ thresholds for discriminating auditory errors. To examine components of the auditory feedback and feedforward control systems, unexpected and sustained (predictable) perturbations to speakers’ auditory feedback can be applied during speech production. Commonly, these perturbations are applied to a speaker’s fundamental frequency ($f_0$), the acoustic correlate of vocal pitch. Unexpected perturbations in feedback (yielding “reflexive” responses) allow for assessment of the feedback control system, whereas sustained perturbations in feedback (yielding “adaptive” responses) allow for assessment of auditory-motor integration. Both unexpected and sustained modifications to auditory feedback of vocal pitch yield robust responses in speakers with typical speech, in which they tend to compensate by opposing the direction of the perturbation.

A few investigations to date have implicated disruptions to disparate aspects of central auditory processing in speakers with HVDs. Two studies have documented a difference in the detection of auditory errors in HVDs, reporting that speakers with HVDs show a reduced ability to discriminate the pitch of pure tones as well as their own vocal pitch compared to controls. When examining reflexive $f_0$ responses, Ziethe et al found larger responses in speakers with HVDs ($N = 10$) compared to controls; yet a recent investigation in a larger sample of speakers with HVDs ($N = 62$) and a higher degree of experimental control reported no group differences (Abur et al. Two studies have also reported evidence of deficits in auditory-motor integration of vocal pitch in HVDs via atypical adaptive $f_0$ responses. In contrast to typical speakers, who demonstrate responses opposing the direction of the pitch shift, many speakers with HVDs show atypically large opposing responses, minimal responses (no pitch changes), or even “following” responses in the direction of the pitch shift. Of note, the one study that examined all three components of auditory-motor control in the same speakers with HVDs reported a relationship between worse auditory discrimination thresholds (reduced ability to detect auditory errors in vocal pitch) and atypical auditory-motor integration, directly linking auditory errors in vocal pitch and atypical auditory-motor integration, directly linking auditory errors in vocal pitch and atypical auditory-motor integration.

Behavioral voice therapy is currently the primary treatment approach for HVDs, but therapeutic effectiveness can vary greatly. Despite high individual variability, voice therapy can effectively relieve voice symptoms for some individuals with HVDs, as quantified by acoustic, aerodynamic, perceptual, and patient self-report measures. In the short-term, voice therapy typically results in improved vocal function; however, relapses and recurrences of voice symptoms are frequent (reported prevalence of 51–68%). Thus, a clear understanding of HVD etiology would greatly improve global therapeutic effectiveness.

Current behavioral therapies for HVDs primarily target musculoskeletal symptoms, vocal function, and respiratory function. A review of the literature determined that the majority of reported therapies for HVDs involved techniques to reduce elevated subglottal pressure during speech, change voice $f_0$, reduce perceived voice roughness, and increase maximum phonation time (the longest amount of time voice can be sustained on a single breath). These therapy goals are often achieved through semi-occluded vocal tract exercises, resonant voice therapies, flow phonation, and manual laryngeal therapy. Although strategies used in voice therapy for HVDs can include an auditory component, eg, use of altered auditory feedback (delayed auditory feedback, masking) or patients’ auditory-perceptual evaluations of their own productions, such approaches are not universally or uniformly applied. Considering the evidence for auditory deviations in HVDs, the goal of the current work was to explore whether voice therapy for HVDs impacts auditory-motor control. Behavioral voice therapy is a common treatment option for speakers with HVDs, but often individuals may require several rounds of therapy because voice symptoms commonly persist or reoccur. It is also not clear whether voice therapy induces neuroplasticity and alleviates the...
observed disruptions to auditory-motor control, or whether therapy results in temporary compensatory strategies that only benefit voice symptoms.

The purpose of the current work was to determine the effect of behavioral voice therapy on auditory-motor control of $f_0$ in HVDs. To examine this question, comprehensive measures of auditory-motor control were assessed within the same speakers before and after voice therapy. These measures of auditory-motor control included (1) auditory discrimination of voice $f_0$, (2) reflexive $f_0$ responses, and (3) adaptive $f_0$ responses. Given the previous findings of disrupted auditory discrimination of $f_0$ and concurrent atypical adaptive $f_0$ responses in HVDs, it was expected that, relative to pretherapy, behavioral voice therapy would result in (1) better auditory discrimination (via reduced acuity thresholds), (2) no differences in reflexive $f_0$ responses (as no disruptions were observed pretherapy in prior work; see Abur et al\textsuperscript{[20]}), and (3) more typical adaptive $f_0$ responses.

### METHOD

#### Participants

A total of 11 individuals with HVDs participated pre and postvoice therapy. The group characteristics are listed in Table 1. Participants labeled “singers” had at least 5 years of formal training in vocal performance. All individuals with HVDs were diagnosed by a laryngologist with either NPVH or PVH based on a comprehensive voice evaluation including videolaryngoscopy at either the Boston Medical Center (Boston, MA) or the Massachusetts General Hospital Voice Center (Boston, MA). Per standard clinical practice, therapy was individualized based on clinical judgment and patient needs. Hence, participants underwent between 4 and 16 weekly sessions of voice therapy across 1–5 months (see Table 1). For the participants with PVH, two speakers included in the study underwent surgical interventions to remove the lesions followed by voice therapy and post-therapy evaluations reported reduced evidence of phonotrauma via videolaryngoscopy. These participants were still included in the study since due to the expected impact of hearing on auditory processing,\textsuperscript{[55]} all participants underwent hearing threshold testing with insert earphones or headphones on a GSI 17 or GSI 18 audiometer (Grason-Stadler, Littleton, MA). Participants were included if they had hearing thresholds of 25 dB HL or below at 250, 500, 1000, 2000, and 4000 Hz per pure-tone hearing screening guidelines by the.\textsuperscript{[56]} All study participants provided informed consent prior to the study and all experiments were performed in accordance with the Boston University Institutional Review Board.

#### Experimental setup

All participants completed tasks to quantify auditory-motor control at two time points (pre and post-therapy) in a sound-attenuated booth at Boston University. The pre and post-therapy experimental session consisted of the same tasks. Each session lasted 2–3 hours and included the following experimental tasks: (1) auditory discrimination of voice $f_0$, (2) reflexive $f_0$ responses, and (3) adaptive $f_0$ responses.

For all tasks, an omni-directional ear-set microphone (Shure MX153) was positioned at approximately 45 degrees from the midline and 7 cm away from the corner of the mouth to record all voice signals. The microphone gain was adjusted with a preamplifier (RME Quadmic II) and was digitized with a soundcard (MOTU Ultralite-mk3 Hybrid or RME Fireface UCX). An Eventide Eclipse V4 Harmonizer was used to create experimental shifts in voice fundamental frequency ($f_0$) with a processing delay between 10 and 30 ms.\textsuperscript{[57]} The processed signal was amplified with an earphone amplifier (Behringer Xenyx Q802) and auditory feedback was administered via Etymotic ER-2 insert earphones or Sennheiser HD 280 Pro headphones.

The software and hardware systems were calibrated prior to each experimental session to ensure the correct output intensity for auditory feedback (Figure 1). The experimental setup was...
Data collection

Auditory discrimination

All participants completed an auditory discrimination task at both experimental sessions. At each session, participants were asked to produce a steady /a/ vowel for 2–3 seconds and their voices were recorded with Praat software. A steady 500-ms portion of each produced vowel was used as speaker-specific stimuli for the experiment. The auditory discrimination task consisted of a justnoticeable-difference experiment with a one-up, two-down staircase paradigm that used a 1:1 up-down step-size ratio. This type of paradigm results in a threshold of discrimination (ie, the point at which a speaker can no longer detect differences between stimuli) at 70.71% accuracy. During the listening task, participants were presented with pairs of their own vowel recordings and asked to judge whether the two stimuli sounded the “same” or “different” in terms of their pitch. Each trial consisted of one stimulus that was a reference (the original recording) and one stimulus with a shift in $f_o$, which was applied based on the staircase procedure logic. The original and the pitch-shifted recordings were presented in randomized order for each trial; thus, each trial contained two recordings for comparison. The initial $f_o$ change applied to the shifted stimulus was +50 cents (100 cents are equivalent to one semitone), with a 4-cent change in direction following two correct responses (decreasing) or one incorrect response (increasing). The 4-cent change in direction was based on prior studies, which determined the step size best suited to reach the threshold in the shortest amount of time. In 20% of trials (“catch trials”), the reference stimulus was played twice to ensure attention to the task. Catch trial responses were not used in the staircase logic, but all participants had above chance catch trial accuracy (> 50%). The experiment ended after 10 “reversals” (ie, changes in the direction), which require two correct responses followed by an incorrect response or one incorrect response followed by two correct responses.

Reflexive and adaptive responses

During the tasks to elicit reflexive and adaptive $f_o$ responses, participants were actively voicing while their auditory feedback was experimentally manipulated (Figure 1). For both tasks, participants were instructed to sustain a steady /a/ vowel for 2–3 seconds for 108 trials per condition. The inter-trial interval was randomly jittered between 1 and 3 seconds to prevent the participant from using rhythmic cues. For both reflexive and adaptive tasks, each condition lasted 10 minutes.

The reflexive response task consisted of two conditions: shift-up and shift-down. Each condition had 84 trials with typical feedback (amplified +5 dB relative to the microphone signal with no pitch-shifting) and 24 trials with the addition of a sudden pitch shift of either +100 cents (shift-up) or –100 cents (shift-down) in voice $f_o$. To prevent habituation to the shifted feedback, there were always at least three typical feedback trials between each trial that had a pitch shift. During the pitch-shifted trials, voice shifts occurred randomly between 0.5 and 1 second after voicing onset to allow the voice to stabilize before the unexpected feedback shift, and remained for the duration of the trial as in prior work. The two conditions were completed in counterbalanced order across participants.

The adaptive response task consisted of three conditions: shift-up, shift-down, and control. The conditions with pitch shifts (shift-up and shift-down) were completed first or third, in counterbalanced order across participants. The control condition was always completed second. The pitch-shifted conditions involved four ordered phases: “baseline”: 24 trials of typical feedback; “ramp”: 30 trials with gradual increases (shift-up) or decreases (shift-down) of 3.3 cents in the $f_o$ of the auditory feedback each trial; “hold”: 30 trials with the pitch
shifts maintained at +100 cents (shift-up) or −100 cents (shift-down); and “after-effect”: 24 trials of typical feedback. For all shifted trials, the pitch shifts were applied at the beginning of each trial and were maintained for the full period of vocalization.

All participants completed the auditory discrimination task and both the shift-up and shift-down conditions for the adaptive f0 response task. For the reflexive response task, data were collected for nine participants in the shift-up condition and eight participants in the shift-down condition. More specifically, eight participants completed both shift-up and shift-down at both sessions, one additional participant completed only the shift-up condition at both sessions, and two participants were not able to complete either condition due to time constraints in the initial session.

Self-reported voice complaints
Self-reported voice complaints were documented for each speaker at the pre and post-therapy experimental session using the Voice-Related Quality of Life scale V-RQOL. Speakers rated their voice-related problems on a scale of 1 (“not a problem at all”) to 5 (“as bad as it can be”) on 10 voice-related questions, which resulted in an overall score that could range from 10 (no problems) to 50 (all problems are as bad as they can be). The raw scores were standardized to values between 0 and 100, Table 1, with higher standardized scores reflecting a better voice-related quality of life.

Reading task
All participants also completed three speech tasks at the two time points (pre and post-therapy); three prolonged /a/ vowels, three prolonged /i/ vowels, “The Rainbow Passage,” and a 1-minute natural speech sample in response to one of the following prompts: “How did you get here today?”, “Do you have any vacation or travel plans?”, “Tell me how the weather has been lately”; “What did you do last weekend?”. Speech was recorded using an omnidirectional ear-set microphone (Shure MX153) at approximately 45 degrees from the midline and 7 cm away from the corner of the mouth. The microphone gain was adjusted with a preamplifier (RME Quadmic II) and was digitized with a soundcard (MOTU Ultralite-mk3 Hybrid or RME Fireface UCX). Audio recordings were collected using SONAR Artist (Cakewalk, Inc.) software at a sampling rate of 44.1 kHz and resolution of 16 bits.

DATA PROCESSING
Auditory-motor measures
To quantify auditory discrimination, a threshold was calculated for each participant as the average f0 shift values in cents across the last six reversals for each participant. To examine reflexive and adaptive f0 responses, each participant’s voice f0 was calculated for each trial and condition using an autocorrelation method via Praat and custom MATLAB scripts.

For the reflexive responses, the 120–240 ms portion (with 0 ms at the onset of the pitch shift) of each shifted trial was used for analyses, in line with prior work. Each 120–240 ms portion contained voice f0 values sampled every 10 ms and this time range was selected to capture the feedback control system response. Each f0 trace in Hz was converted to cents by using the average across the 100 ms immediately preceding the pitch shift as the reference frequency for each trial. The resulting voice f0 in cents was averaged across all pitch-shifted trials into a single trace for each speaker for each condition (shift-up and shift-down). The average across the f0 values in the 120–240 ms trace was termed as the “reflexive response.”

For the adaptive responses, the 40–120 ms portion of each trial was extracted (with 0 ms corresponding to the start of vocalization) and used for analyses. This region of vocalization was used to capture the feedforward control system response. For all conditions, the average voice f0 across the 40–120 ms region of each trial was extracted in Hz. Then, the average f0 values across the baseline trials in each condition were used as reference frequencies to convert the average f0 for each trial in Hz to cents for each associated condition (shift-up, shift-down, and control). To account for natural variability in voice f0, the control condition was then subtracted from the two pitch-shifted conditions. Given that prior work has observed variable adaptive responses in speakers with HVDs (atypically large opposing responses, no response, and following responses), adaptive responses were examined by a z-score method. Z-Scores were computed by comparing each participant’s adaptive f0 response pre and post-therapy to a previously reported adaptive f0 response mean from a control group (N = 62) using a 90th percentile cutoff value for classification. Using the z-score cutoff values for the shift-up (z = 1.46) and shift-down (z = 1.52) conditions, all participant responses were classified as either “typical” (below the 90th percentile cutoff) or “atypical” (greater than the 90th percentile cutoff).

Consensus Auditory-perceptual Evaluation of Voice
Recorded speech from the reading task was used as stimuli for the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V) rating protocol. For each time point (pre and post-therapy), the set of three /a/ and three /i/ vowel productions, six sentences from “The Rainbow Passage,” and 30 seconds of natural speech were combined into a single recording for each speaker. This yielded two recordings for each speaker. A blinded voice-specializing speech-language pathologist completed the full CAPE-V rating protocol on all types of stimuli, which were presented randomly from the full set of pre and post-therapy recordings (N = 22). Approximately 15% of samples (N = 3/22) were repeated for reliability. The rater showed excellent intra-rater reliability via an interclass correlation coefficient >0.97 for the four rated percepts (overall severity of
RESULTS
The results of the study are reported descriptively for the pre and post-therapy sessions. For auditory discrimination and adaptive response tasks, results are reported for all 11 speakers. For the reflexive responses, two speakers were not able to complete the task and one speaker completed only the shift-up condition due to time constraints (see Methods), so pre and post-therapy data are reported for nine speakers in the shift-up condition and eight speakers in the shift-down condition.

Auditory discrimination
Average auditory discrimination thresholds were 40.1 cents (SD = 19.0 cents) pretherapy and 38.5 cents (SD = 19.4 cents) post-therapy, but there was substantial variability at an individual level (Figure 2 and Table 2). Given differences in auditory discrimination in speakers with HVDs and typical speakers by singing experience,20 results are discussed separately for singers (N = 8) and non-singers (N = 3). Of the eight singers in the study, two singers displayed typical discrimination thresholds at both the pretherapy and post-therapy sessions (Cases 08 and 09; Figure 2) and the remaining six singers displayed atypical discrimination in the pretherapy session (ie, outside of the 95% confidence interval for singers with typical voices who completed the same paradigm in prior work; Abur et al., 2021). Three of the six singers with atypical discrimination pretherapy (Cases 03, 06, and 07) displayed discrimination thresholds within typical range at the post-therapy session, whereas the other three (Cases 01, 04, and 05) still had discrimination thresholds within the atypical range post-therapy (Figure 2). Cases 04 and 05 still demonstrated reduced
discrimination thresholds at post-therapy, demonstrating that auditory discrimination improved even though it did not change to be within the typical range. Thus, five of the six singers with atypical discrimination pretherapy demonstrated improved thresholds post-therapy, but only three of the six singers with atypical discrimination pretherapy demonstrated post-therapy discrimination thresholds within the typical range. Of the three non-singers in the current work, one speaker (Case 10) demonstrated atypical discrimination thresholds, i.e., outside the 95% confidence interval for non-singers with typical voices who completed the same paradigm in prior work. At both sessions and the other two speakers demonstrated discrimination thresholds within the typical range at both sessions (Cases 02 and 11; Figure 2).

**Reflexive \( f_o \) responses**

Given that the reflexive \( f_o \) responses pretherapy did not show statistical differences compared to typical speakers, no changes were expected in reflexive \( f_o \) responses. On average, reflexive \( f_o \) response magnitudes in the 120–240 ms analysis range did not show descriptive differences due to therapy (i.e., the individual responses remained within the bounds of mean and standard deviation interval previously reported in typical speakers for the shift-up condition (\( M = -13 \) cents, \( SD = 13 \) cents) and shift-down condition \( M = 21 \) cents, \( SD = 18 \) cents). The group-level shift-up response for the nine speakers pretherapy (\( M = -20.7 \) cents, \( SD = 13.3 \) cents), shift-up response for the nine speakers posttherapy (\( M = -19.2 \) cents, \( SD = 12.3 \) cents), shift-down response for the eight speakers pretherapy (\( M = 23.6 \) cents, \( SD = 17.7 \) cents), and shift-down response for the eight speakers posttherapy (\( M = 20.1 \) cents, \( SD = 29.4 \) cents) are all displayed in Figure 4.

**Adaptive \( f_o \) responses**

The adaptive \( f_o \) responses for each speaker were classified as “typical” or “atypical” using a z-score method; responses within the 90th percentile of a 62-speaker control group were considered “typical” see methods in Abur et al. In the pretherapy session, five speakers demonstrated atypical adaptive responses (outside the z-score cutoff value; see Methods). Three speakers had atypical responses for the shift-down direction (two singers, one non-singer), one speaker (non-singer) had an atypical response for the shift-up direction, and one speaker (singer) had an atypical response in both the shift-up and shift-down directions. The remaining five speakers had typical responses in both shift directions. At the post-therapy session, all five speakers with atypical adaptive responses pretherapy demonstrated improvements post-therapy (Figure 4 and Table 2). For four of the five speakers with atypical adaptive \( f_o \) responses pretherapy, the post-therapy adaptive responses were below the cutoff for a typical response. One speaker with an atypical response to both shift-up and shift-down conditions pretherapy demonstrated a typical response for the shift-up post-therapy, but still displayed an atypical response the shift-down post-therapy; however, the shift-down response post-therapy showed improvement compared to the pretherapy session as evidenced by a z-score closer to the cutoff value.

**Self-reported voice complaints**

On average, the group demonstrated improved standardized V-RQOL scores from pre-therapy (\( M = 72.7\), \( SD = 13.0\)) to post-therapy (\( M = 91.8\), \( SD = 4.2\)). The group-level improvement was greater than the minimally clinically important difference (i.e., reflecting improved vocal function) reported in prior work \( M = 18.6\) with an \( SD = 12.7\), based on patient’s self-report of voice quality pre and post-therapy. The range of standardized scores pretherapy was 52.5–95.0 and the range of scores posttherapy was 82.5–97.5. At an individual level, 10 of the 11 speakers demonstrated decreases in V-RQOL score post-therapy, indicating an improvement in self-reported voice problems (Figure 5 and Table 2). One speaker with minimal self-reported voice problems pretherapy (standardized V-RQOL score of 95) demonstrated no changes in
V-RQOL score pre- compared to post-therapy (dark blue square in Figure 5).

Consensus Auditory-Perceptual Evaluation of Voice
The group-level CAPE-V ratings decreased for all percepts. On average, overall severity of voice ratings decreased from 17.1 mm pretherapy to 14.2 mm post-therapy, roughness ratings decreased from 14.5 mm pretherapy to 10.8 mm post-therapy, breathiness ratings decreased from 11.8 to 8.2 mm, and strain ratings decreased from 8.1 to 7.5 mm. Overall, CAPE-V ratings were in the lower range at both pre and post-therapy sessions (< 30/100 mm for 10 speakers and < 50/100 mm for one speaker), which indicates mild perceptual dysphonia at a group level. The pre and post-therapy session CAPE-V ratings ranged from 0.3 to 11.6 mm. Six of the 11 speakers demonstrated decreased overall severity of dysphonia ratings (ie, improved) post-therapy and five speakers, who had low overall severity ratings pretherapy (< 25 mm), demonstrated minimal changes post-therapy (< 5 mm in either direction; Figure 6 and Table 2).

DISCUSSION
The goal of this case-series study was to assess whether voice therapy resulted in improvements to auditory discrimination and auditory-motor control in speakers with HVDs. This is the first report of a comprehensive assessment of the auditory-motor control system (ie, auditory discrimination, reflexive responses, and adaptive responses) in any speech disorder before and after therapeutic intervention. Additionally, this work examined auditory-motor measures together with patient self-reported voice problems and expert auditory-perceptual judgements of overall voice severity to provide a multi-factorial assessment of voice changes post-therapy.

The self-reported voice problems via the V-RQOL and expert clinical judgements of voice (CAPE-V overall severity of dysphonia) support that vocal function improved for participants in the study. Ten of the 11 speakers demonstrated improvements in either VRQOL or CAPE-V ratings. The remaining speaker had minimal voice complaints (standardized VRQOL score = 95) and mild perceptual voice severity at both sessions (24.6–28.7 mm on the CAPE-V).

Previous work has examined one component of auditory-motor control (reflexive \( f_o \) responses) pre and post-therapy in a similarly small sample (N = 12) of speakers with Parkinson’s disease. Speakers with Parkinson’s disease demonstrated an atypically large response, on average, to reflexive perturbations of \( f_o \) compared to controls at a pretherapy session. Following speech therapy focused on improving vocal intensity (LSVT LOUD, the speakers with Parkinson’s disease demonstrated improvements in reflexive \( f_o \) responses (reduced magnitudes). This finding supports the possibility that disrupted auditory-motor measures involving speech production could become more typical following voice therapy. However, Li et al did not investigate measures of auditory discrimination, auditory feedback integration (adaptive \( f_o \) responses), self-perceived voice symptoms, or auditory-perceptual judgments of voice by a clinician. The lack of these additional measures limits the interpretation of which specific mechanisms might have benefited from the therapeutic intervention in Li et al.71 As posited by the DIVA model and supported by neurophysiological studies, measures of auditory discrimination reflect error sensitivity, reflexive responses to sudden changes reflect feedback control of speech, and adaptive responses to predictable change reflect feedforward control of speech (incorporation of errors and motor learning). Thus, the inclusion of these three measures in the current study, together with self-reported voice complaints and clinical judgements, yields a comprehensive assessment of speech motor control in the auditory domain to more fully interpret the impact of therapy.

FIGURE 5. Self-reported voice-related quality of life scores pre and post-therapy.

FIGURE 6. Overall severity of dysphonia ratings from 0 (no dysphonia) to 100 (maximum severity) for the pre and post-therapy sessions.
varied at an individual level for the 11 speakers examined pre and post-therapy (Figure 6). Given the heterogeneity in HVDs, the variability in the degree of improvement post-therapy in the current sample is not surprising. Findings are discussed for each experimental assessment below.

Auditory-motor improvements following voice therapy

The results for auditory discrimination were variable across speakers in the current work, but a subset of speakers who had disruptions to auditory discrimination demonstrated improvements post-therapy. Four of the 11 speakers did not show atypical discrimination thresholds either pre or post-therapy, whereas seven speakers showed atypical discrimination thresholds at the pretherapy session (based on previous data on typical speakers by singing experience; Figure 2). Of the seven speakers with atypical discrimination thresholds pretherapy, three speakers demonstrated typical responses post-therapy and two speakers demonstrated some improvements (thresholds closer to the typical range). The variability in individual improvements in auditory discrimination is not entirely unexpected since current voice therapy techniques for HVDs do not uniformly employ an auditory component. Prior work has demonstrated that an auditory discrimination training task together with passive stimuli exposure is an effective method to induce auditory learning in speakers without voice disorders; thus, future work could explore whether similar paradigms could benefit auditory function in HVDs. For two of the five speakers who demonstrated improved auditory discrimination post-therapy, adaptive responses also improved (atypical adaptive responses became typical adaptive responses), which suggests that auditory-motor control changes may relate to changes in auditory mechanisms for some speakers.

Reflexive $f_o$ responses at the pretherapy sessions were within the typical range for the nine speakers who completed the shift-up condition and the eight speakers who completed the shift-down condition; hence, no changes were expected for this measure post-therapy. Descriptively, the group averages demonstrated minimal differences between the pre and post-therapy sessions. Previous work has observed larger reflexive $f_o$ response magnitudes in individuals with HVDs compared to typical speakers, but substantial differences in methodology prevent a direct comparison to the current work see Abur et al for a review. Although there were no qualitative differences noted after therapy in the current work, both the pre and post-therapy reflexive $f_o$ responses for the shift-down direction were qualitatively more variable compared to the shift-up direction, as shown by the larger standard deviation bars (Figure 3). This lends further support to the notion that shift direction is an important consideration for measures of reflexive $f_o$ response, as observed in prior work. The similar results for reflexive $f_o$ responses across sessions in the current speaker sample also provide support for the replicability of reflexive response measures over time.

The adaptive $f_o$ responses, which are thought to reflect the incorporation of changes in auditory feedback into voice production over time, showed improvements post-therapy for all five of the speakers who demonstrated atypical responses pretherapy (Figure 4 and Table 2). For the shift-up condition, 2/11 (18%) of speakers demonstrated atypical adaptive responses pretherapy and for the shift-down condition, 4/11 (36%) of speakers demonstrated atypical responses pretherapy. These incidence rates of atypical adaptive responses are in line with those previously reported in the larger group of 62 speakers with HVDs (17% for shift-up and 30% for shift-down). The overall improvement in adaptive responses in the current work provides promising evidence that auditory-motor control (ie, the integration of auditory feedback into voice production) can improve with voice therapy, adding to prior work that found evidence of improved auditory feedback processing (via reflexive $f_o$ responses) in Parkinson’s disease following voice therapy. It is important to note that improved adaptive $f_o$ responses may result from several mechanisms, and the current work did not examine detailed laryngeal-level information (eg, vocal fold kinematics). Therefore, the contributions of sensory changes (ie, auditory, somatosensory) compared to motor improvements following voice therapy in HVDs cannot be determined here and should be explored in future studies.

Summary of auditory-motor findings

The auditory-motor findings provide preliminary evidence that therapeutic protocols may improve auditory-motor control for some speakers while also supporting the systematic inclusion of auditory processing-related strategies in voice therapy. The subset of post-therapy improvements in auditory discrimination as well as adaptive responses suggest that current strategies for voice therapy do not universally improve auditory-motor function. Hence, inclusion of a more formal auditory training component for individuals with HVDs who display atypical pretreatment auditory responses could be beneficial. Specifically, employing auditory discrimination tasks and passive stimuli exposure (ie, speakers passively listening to the recordings of their own voice from the discrimination task), separately, may be effective methods to induce auditory learning based on evidence from prior work. Although post-therapy improvements in auditory-motor control were found in a subset of the current sample, it remains unclear how long the observed improvements may last. This possibility should be explored in additional studies by examining the degree to which improvements in auditory-motor measures post-therapy remain at follow-up sessions (eg, after 6 months).

Relation of auditory-motor findings to self-reported voice complaints and clinical voice ratings

At a group-level, the auditory-motor improvements were accompanied by changes in self-reported voice complaints (via V-RQoL ratings) or CAPE-V ratings of overall voice
severity. For the auditory discrimination task, two of the three speakers with discrimination thresholds that changed from atypical to typical post-therapy showed concurrent improvements to CAPE-V ratings. This finding suggests that better discrimination thresholds may relate to improved vocal quality. For the adaptive responses, four of the five speakers who had atypical responses pre-therapy that improved in the post-therapy session demonstrated concurrent improvements in CAPE-V ratings (Figure 6). This result strengthens previous evidence that adaptive responses are associated with auditory-perceptual measures of speech function.63

Limitations
This case series is a descriptive report of auditory-motor measures pre and post-therapy in HVDs that provides important preliminary data, but there are limitations. Notably, this work only included 11 speakers with HVDs pre and post-voice therapy. Hence, the results from this case-series report can be used as a basis to inform future investigations in a larger sample of speakers with HVDs that can yield statistical support for the relationships between the current experimental variables. Further, a control group was not included, so this work cannot fully rule out the possibility of additional variables that may contribute to changes in auditory-motor control over time.

In terms of the sample, the 11 speakers included here may not be generalizable to the larger population of individuals with HVDs for several reasons. All speakers in this case series had voice complaints pretherapy and were diagnosed with an HVD. However, the pretherapy CAPE-V ratings of overall severity of dysphonia were mild (group average of 17.1/100 mm), indicating more mild dysphonia compared to prior investigations in speakers with HVDs (eg, average severity of dysphonia ratings from 10 speakers with MTD = 79.3/100 mm66 and from 111 speakers with MTD = 67.9/100 mm67). This may be a result of the case-series sample consisting of mostly singers (N = 9), who are at higher risk of developing HVDs and who show greater sensitivity to changes in their vocal pitch compared to nonsingers, ie, singers have better discrimination thresholds of self-produced vocal pitch compared to non-singers.20

There are also limitations related to the components of voice therapy. The speakers in the current study did not complete the exact same therapy protocol due to the need to personalize therapy based on specific voice symptoms in line with prior research in HVDs.68 However, comparisons of detailed therapeutic techniques and their impact on auditory-motor control improvements in HVDs could be important considerations for subsequent studies. In addition to possible confounds of individualized therapy, speakers also did not undergo the same number of therapy sessions since symptom resolution naturally occurred at different time points. Descriptively, the speakers with more therapy sessions did not appear to demonstrate better voice improvements in this case-series report, in line with prior findings that higher therapy dosage does not always correspond to therapeutic effectiveness.42

Another source of variability in speakers with HVDs is related to differences in laryngeal kinematics, somatosensation, and aerodynamic function, none of which were included in the current investigation. Future work should examine these measures together with auditory-motor measures in speakers with HVDs.

Finally, a single rater completed clinical ratings in this work on a set of speech stimuli that did not include CAPE-V sentences, which could limit the generalizability of the auditory-perceptual assessment. Having a single rater was a deliberate choice to mirror a clinical setting, wherein one clinician makes a pre and post-therapy assessment of a patient’s voice. However, this design choice, together with the stimuli, may not be fully representative of a larger population of clinical raters.

Conclusion
In sum, the case series reported here is the first investigation of the impact of voice therapy on all components of auditory-motor control; specifically, in speakers with HVDs. Ten of the 11 patients with HVDs included in this case series demonstrated improvements in voice via either self-reported voice complaints or expert clinical judgements of overall severity of dysphonia. Eight of the 11 patients demonstrated improvements in either auditory discrimination, adaptive f0, responses, or both. These findings support the benefits of voice therapy in individuals with HVDs and highlight the benefit of considering auditory discrimination and auditory-motor control measures in assessment and therapy for HVDs.

Declaration of Competing Interest
Robert E. Hillman has financial interests in InnoVoyce LLC (board membership), a company focused on developing and commercializing technologies for the prevention, diagnosis, and treatment of voice-related disorders. His interests were reviewed and are managed by Massachusetts General Hospital and Mass General Brigham in accordance with their conflict of interest policies. The other authors have no relevant conflicts of interest to declare.

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References


