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The Effect of Pitch and Loudness Auditory Feedback Perturbations on Vocal Quality During Sustained Phonation

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Summary: Objective. Dysphonia is a reduction in vocal quality that impacts communication and is often an early sign of a voice disorder. There is little information regarding the effects of auditory feedback control of loudness and pitch on voice quality. In this study, we used both loudness-shift and pitch-shift paradigms to study the relationship between auditory feedback control and vocal quality as measured by smoothed cepstral peak prominence (CPPS), which reflects the harmonicity of the voice signal.

Study Design. Experimental, mixed design.

Methods. We applied 200 ms loudness-shifts (± 0, 3, or 6 dB) and pitch-shifts (± 0, 50, and 100 cents) to auditory feedback during sustained vowel production in 25 healthy adults. We then measured CPPS before and after the loudness-shift or pitch-shift to investigate the effect of changes in auditory feedback on vocal harmonicity.

Results & Conclusions. Results showed that, on average, CPPS significantly decreased between the first half of the measured segment and the last half of the segment in the absence of auditory feedback shifts, suggesting that voice quality may be reduced across longer vowels over time. Upward and downward shifts in loudness auditory feedback caused a relative increase in CPPS, indicating an improvement in vocal harmonicity, even in cases when vocal intensity was reduced. Pitch alterations had inconsistent and minimal effects. We propose that there may be a control mechanism for voice quality that increases harmonicity of the voice signal to improve voice audibility (ie, ability to be heard) in the presence of unpredictable variability in voice intensity.

Key Words: Auditory feedback—Cepstral peak prominence—Loudness—Pitch—Smoothed Voice quality.

INTRODUCTION

Vocal quality, in addition to loudness and pitch, is one of the main perceptual properties of voice.[1] Dysphonia is an alteration in vocal quality, loudness, or pitch that impacts communication and quality of life in affected populations and is often pathognomonic to voice disorders.[2] Many voice therapy techniques treat dysphonia by modulating the loudness and pitch of the voice to improve glottal efficiency.[3,4] In these treatments, a focus is placed on auditory and kinesthetic awareness of loudness and pitch to improve vocal control.[3–5] However, there is currently little known about the role of sensory feedback in voice quality control. Auditory feedback control of voice is complex, involving the monitoring of multiple parameters such as roughness, breathiness, pitch, and loudness.[6,7] Numerous studies have shown that when errors are identified in loudness or pitch feedback, a reflexive response in loudness or pitch is initiated to correct for the perceived error.[6,8] However, little is known about the interplay among feedback control of these vocal parameters when errors in one parameter are identified. For example, there is evidence that both loudness and pitch are affected when there are perceived errors in pitch auditory feedback.[9] This demonstrates that there is an interplay between auditory feedback control of loudness and pitch. In this study, we extended the investigation of auditory feedback control of voice by examining how the reflexive correction of loudness and pitch errors affect aspects of vocal quality and harmonicity. Harmonicity refers to the regularity of frequency components in a harmonic structure.[10,11] We utilized both loudness-shift and pitch-shift paradigms to investigate how harmonicity is affected by changes in loudness and pitch auditory feedback.

Loudness-shift and pitch-shift paradigms

In the loudness-shift and pitch-shift paradigms, participants hear their voice feedback shifted upward or downward in loudness or pitch. Participants automatically respond with a change in voice intensity or fundamental frequency (f_o) output referred to as a loudness-shift or pitch-shift response, respectively.[6,12] For pitch-shift responses, the resulting vocal response is thought to be reflexive in nature because of the speed with which it occurs following the pitch-shift stimulus and the participants' inability to volitionally control it.[6] The majority of pitch-shift responses occur in the opposite direction of the feedback perturbations and are termed opposing responses.[6,8,9] A minority of responses follow the shift direction and are termed following responses.[6,8,9,12] Some

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theories posit that opposing responses indicate that the participant is using an internal reference for pitch control, and following responses indicate that the participant is using an external reference; however, the differential mechanisms behind these responses are still unknown.[8,13,14] Responses to loudness-shifted feedback follow a similar pattern of opposing and following the shift direction and are also theorized to be reflexive in nature.[9,12] Overall, both the loudness-shift and pitch-shift paradigms are useful experimental approaches to study the role of auditory feedback on voice control. In this study, we were interested in how responses to loudness-shifted and pitch-shifted auditory feedback affect vocal quality.

Cepstral peak prominence

Acoustic analysis has long been used to track and measure changes in vocal quality.[15] Recent evidence has suggested that the Smoothed Cepstral Peak Prominence (CPPS) is the most robust measure of dysphonia severity and that it is highly correlated with perceptual ratings for changes in vocal quality.[16−18] CPPS is a modification of the cepstral peak prominence algorithm used to measure signal harmonicity.[19] Cepstral peaks are identified in a Fourier Analysis to examine harmonicity within the frequency spectrum.[20] The CPPS method involves smoothing (ie, averaging) the cepstra in the Fourier Analysis before identifying the cepstral peak prominence, resulting in improvement in prediction accuracy between acoustic analysis and perceptual measures.[17,18] A low measure of CPPS indicates that the signal has an indistinct harmonic structure[21] and is strongly correlated with perceptual features of breathiness and roughness.[17,22,23] A high measure of CPPS indicates a clear harmonic structure and a perceptually normal or pressed voice quality.[17,22,23]

Predictions

Our primary interest was how correction of loudness and pitch through auditory feedback control affects vocal quality and vocal harmonicity. We were also interested in whether loudness-shifts or pitch-shifts affect vocal harmonicity differently. We investigated these questions by separately applying loudness-shifts and pitch-shifts to sustained vowel productions. Typically, the measurement of interest in studies that utilize auditory feedback shifts is the reflexive vocal response that occurs rapidly after the shift. The reflexive vocal responses were measured in a prior study and are reported in a separate paper for simplicity and succinctness.[24] In this paper, the measurement of interest was the change in CPPS pre- and post-perturbation. We predicted that loudness-shifts would significantly affect vocal harmonicity, but that pitch-shifts would not due to the differential physiological mechanisms involved in loudness and pitch control.

During sustained phonation, the respiratory system coordinates with the intrinsic laryngeal muscles to control subglottal pressure and alter the loudness and pitch of the voice.[21,22,25−27] Louder voicing often involves increased subglottal pressure achieved by greater respiratory flow and increased adduction of the vocal folds, resulting in greater amplitude of vocal fold vibration.[27] Softer voicing may be correlated with a perceptually breathy voice quality caused by the escape of air from the glottis with the vocal folds in a slightly more abducted position than in louder phonation.[15] Previous research has suggested that vocal loudness has a significant effect on measures of CPPS.[15] Thus, changes in vocal loudness may influence the degree of harmonicity of the voice signal and subsequent cepstral measures, causing CPPS to increase as vocal intensity increases.[15]

The primary control of f_o is thought to be based on the differential activation of the cricothyroid (CT) and the thyroarytenoid (TA) muscles in coordination with functions of the respiratory system.[27,28] These intrinsic laryngeal muscles tend to contract more forcefully to vocalize at higher pitches.[29] Varying degrees of simultaneous contraction of the CT and TA muscles during voicing allows for the flexibility of pitch control in the human voice.[30] There is a paucity of information regarding the effects of pitch on measures of CPPS. A recent study suggested that CPPS increases in higher f_o voicing in disordered voices.[21] Sampaio and colleagues suggested that the participants may have used strained and louder phonation to produce higher pitches in their study, leading to increased medial compression of the vocal folds and higher measures of CPPS.[15,21] However, it is unclear whether a similar effect would be observed in a nondysphonic population. It is possible that pitch-shifts in auditory feedback that result in increased f_o would increase CPPS and vocal harmonicity because vocal fold lengthening, which involves CT contraction in coordination with TA activation[30] and adjustments in other laryngeal and respiratory muscles, also contributes to vocal fold adduction.[27,31] However, there are multiple laryngeal muscle activation pathways that can be used to control f_o which compounds the difficulty of predicting the effect of pitch on CPPS.[32] Additionally, pitch-shifts resulting in slight changes in f_o may not significantly affect vocal harmonicity in nondysphonic voices because participants may not use the same muscular force to produce higher pitches observed in disordered voices.[2] Given limited information from previous research, we were unable to make a clear prediction of the effects of pitch-shifts on CPPS.

Therefore, when comparing the differential effects of loudness-shifts vs. pitch-shifts on vocal quality, we predicted that loudness-shifts would result in a greater change in CPPS than pitch-shifts. Our reasoning was as follows: Changes in glottal adduction, amplitude of vocal fold vibration, and subglottal pressure associated with changes in vocal intensity are likely to lead to significant changes in measures of CPPS. However, the muscles responsible for pitch changes, although associated with slight glottal adduction, are not the primary muscles of glottal adduction and would likely have less of an effect on CPPS. If this prediction is true, it would support our hypothesis that changes in auditory feedback of vocal loudness affect characteristics of vocal quality because of the relationship between glottal adduction, subglottal pressure, and vocal fold vibration. Overall, our research question was as follows: Is vocal quality affected by changes in auditory feedback? If so, do measures of CPPS follow the expected pattern given the physiological production of loudness and pitch changes? Given the insights into neural control of the voice derived from the loudness-shift response,[9,12,33] changes in CPPS which are not reflective of the physiology of loudness or pitch may provide information about the underlying auditory-motor mechanisms that control voice quality.

METHODS

Participants

Twenty-five Northwestern University students participated in the study (18-35 years of age) (3 women, 22 men). Data from these participants were also analyzed in a recent research study.[24] All participants passed a pure-tone hearing screening using a Beltone Audiometer (Model 119) according to the American Speech-Language-Hearing Association's guidelines (25 dB HL at octave intervals between 1000 and 4000 Hz).[34] All participants reported English as their native language and denied a history of speech, language, or neurological disorders. This study was approved by the Northwestern University Institutional Review Board.

Apparatus

After obtaining consent and completing the hearing screening, participants were seated in a double-walled, sound-treated booth (IAC, Model 1201). Participants wore Sennheiser headphones (model HMD 280) and vocalized into an attached AKG microphone (model C420) that was positioned approximately 2.54 centimeters from the angle of the mouth. The microphone signal was amplified and digitized by a MOTU Ultralite mk3 and routed using Cue Mix software. Signals were perturbed by an Eventide Eclipse Harmonizer. The timing of the feedback perturbation was controlled by MIDI software (Max MSP 5.0, CueMix FX). The auditory feedback was amplified using an Aphex Headpod 4 Amplifier. The overall frequency response of this recording chain, including the AKG microphone, MOTU Ultralite mk3, Cue Mix FX, Eventide Eclipse Harmonizer, and the Aphex Headpod, was estimated to be about 20 Hz-20 kHz with a $\pm$ 1 dB attenuation. We would expect negligible distortion of the sound signal that is expected with this acoustic equipment.

Output from a simplified sound level meter in MIDI software was displayed on a computer screen to aid in the maintenance of a consistent intensity level of approximately 73-75 dB SPL. In order to mask the participant's bone-conducted feedback, a gain of 10 dB SPL was applied to the headphone auditory feedback of the participant's voice resulting in an auditory feedback of about 83-85 dB SPL. We were unable to quantify how well this 10 dB boost fully masks bone conduction feedback, however, past research has shown that the magnitude of the vocal responses is effectively elicited by as low as a +5 dB boost.[6,35] Calibrations were completed using a Brüel & Kjær sound level meter (type 2250), a set of in-ear microphones (model 4101-A), and a prepolarized free-field microphone (type 4189) to calibrate the gain between microphone input and headphone output with a 1 kHz sinusoidal pure tone. It should be noted that with all auditory feedback perturbation paradigms, there is a small feedback delay due to hardware and software capabilities. The software delay in the current study was 14 ms, which was measured as the time from onset of the microphone signal at the recording computer (after being routed to the MOTU) to the onset of the MOTU output signal that was perturbed by the Eventide Eclipse Harmonizer. This represents the software latency only and does not account for the input or output hardware latencies. There is likely an additional hardware delay that could add around a 15 ms delay.[36] Recent research has demonstrated that experimental equipment delays below 100 ms do not have a significant effect on pitch-shift paradigms.[35]

The perturbed auditory feedback heard by the participants, the true vocal output of the participants, and the timing markers for perturbation onset were obtained using a multi-channel recording system (AD Instruments, model ML880, PowerLab A/D converter) with LabChart software (AD Instruments, v.7.0) to align the timing markers with participant voice output for later data analysis using Igor Pro 6 (Wavemetrics, Inc., Lake Oswego, Oregon). The time-aligned markers allowed for the determination of the perturbation timing (onset and offset) and direction (upward or downward).

Procedures

Participants followed visual prompts on a computer screen which consisted of the text "say ah" and "stop." The text "say ah" initiated the trial and "stop" was presented 5 seconds after voice onset. Participants performed the target vocalizations in four blocks of trials. There were two blocks of loudness perturbations and two blocks of pitch perturbations. Block order was partially randomized so that no two loudness perturbation blocks or two pitch perturbation blocks occurred consecutively while still minimizing the block order effects described in Scheerer and Jones.[37] "Block 1" consisted of +100 cent, −50 cent, and control (0 cent) conditions; "Block 2" consisted of +50 cent, −100 cent, and control (0 cent) conditions; "Block 3" consisted of +6 dB, −3 dB, and control (0 dB) conditions; and "Block 4" consisted of +3 dB, −6 dB, and control (0 dB) conditions. Participants were offered rest breaks and water between each block. In each block, participants held an /ɑ/ sound for approximately 6 seconds with five perturbations presented per vocalization. In previous studies, the application of multiple perturbations per vocalization yielded identical results compared to when one perturbation was applied per vocalization.[12,38] Each vocalization was considered a trial, and there were 18 trials per block. With 18 trials per block, and five perturbations per trial, there were a total of 90 perturbations presented within each block. Within the 90 perturbations, there were 30 perturbations per experimental condition for the block. For example, in "Block 1," there were 30 perturbations at +100 cents, 30 perturbations at −50 cents, and 30 perturbations at 0 cents (control trials). Overall, there were 8 experimental conditions collected throughout the 4 blocks of the experiment (2 loudness perturbations levels x 2 pitch perturbation levels x 2 perturbation directions).

Before starting, the task was explained by the experimenter, and participants were instructed to keep their voice as steady as possible. Participants were cued by the monitor in the sound booth with a red light and a green light; when the green light illuminated, participants could begin saying /ɑ/ when they were ready, and participants would continue vocalizing until the red light flashed. Practice trials prior to the experimental trials confirmed that all participants were able to differentiate these two colors and follow the instructions. Each vocalization required producing the /ɑ/ sound for a maximum of 6 seconds while five perturbations were presented. The first perturbation was presented randomly between 500 ms and 700 ms after voice onset, and the subsequent four perturbations occurred randomly between 700 ms and 900 ms after the prior perturbation. Each perturbation had a duration of 200 ms, and the condition order was determined randomly.

Analysis

An analysis of the loudness-shift and pitch-shift responses was completed in a prior analysis.[24] From that prior analysis, information about the direction of the vocal responses was used in this current study. For example, if a vocal response opposed the direction of the shift (eg, upward pitch-shift, downward pitch-shift response), the response was labeled as "opposing." Vocal responses that followed the direction of the shift were labeled as "following." Response direction was important to include in this study to determine not only if the shift direction had an effect on CPPS, but if the response direction also had an effect.

To compare changes in CPPS due to the loudness- or pitch-shifts, we extracted CPPS from preperturbation and postperturbation windows using Praat software.[39] There were two windows of analysis: the pre-perturbation window from −300 ms to 0 (0 being on the onset of the perturbation) and the postperturbation window from 0 to 300 ms which included the 200 ms perturbation and 100 ms after the perturbation. CPPS was measured in the preperturbation and the postperturbation windows using a custom Praat script modeled from Maryn and Weenink.[40] For detailed information on the analysis, please refer to Lopes et al.[19] In the present analysis, CPPS was derived from the cepstrum in both windows. To measure the change in CPPS in the post-perturbation window compared to the preperturbation window, we calculated a difference value for each trial by subtracting the CPPS value of the preperturbation window from the CPPS value of the postperturbation window. The difference value, henceforth termed CPPS_DIFF, was used as the dependent variable in the following statistical analyses.

As previously stated, in the present analysis CPPS was derived from the cepstrum in the preperturbation window and the postperturbation window. The cepstrum has been described as a log power spectrum of a log power spectrum with a resulting graph with the time ("quefrency") on the on the x-axis and "cepstral magnitude" on the y-axis.[17,18] The cepstrum appears as a line with many peaks and valleys, and the highest peak is labeled the cepstral peak. A linear regression line is drawn, relating quefrency (time) to cepstral magnitude.[18] Cepstral peak prominence (CPP) is a single value which represents the distance (difference) between the peak and the corresponding point on the regression line below the peak.[41] The regression line defines all noise surrounding the peak. Thus, the higher the peak emerges from this noise (ie, the greater the CPP value) the better the voice quality is.[17,41] CPPS is an additional processing step that involves smoothing (ie, averaging) the cepstra before identifying the cepstral peak and the difference between the highest peak and the regression line.[18] The following figure (Figure 1) illustrates the relationship between the regression line and cepstral peak in a CPPS calculation.

We used R[42] and *lme4*[43] to build two linear mixed effect regression models (one for loudness-shifts and one for pitch-shifts) of the relationships between CPPS_DIFF, shift magnitude (±0, 3, and 6 dB; or ±0, 50, and 100 cents), and response direction (opposing, following, and control trials). In these models CPPS_DIFF was the dependent variable, shift magnitude, and response direction were entered as combined fixed effects, and random intercepts were included by participant. *P* values and degrees of freedom were obtained using the package *lmertest*[44] which estimates *P*-values via *t* tests using the Satterthwaite approximations to degrees of freedom. Posthoc comparisons were made using Tukey contrasts from the "emmeans" function in the *emmeans* package that automatically adjusted for multiple comparisons.[45]

RESULTS

Our first research question asked whether CPPS is affected by the presence of loudness-shifts compared to control trials (ie, trials without loudness-shifts). Table 1 displays the model output for a linear mixed effects regression model with CPPS_DIFF as the dependent variable, loudness-shift magnitude, and response direction as the fixed effects, and a random intercept by participant. In this model, the regression estimate for the intercept displays CPPS_DIFF for control trials, or how much CPPS values changed between two measurement windows without feedback shifts present. The significant effect for the intercept (ie, control trials) indicates that in the presence of no loudness-shifts, CPPS decreased by 0.24 dB (SE = 0.04) in the post-perturbation window

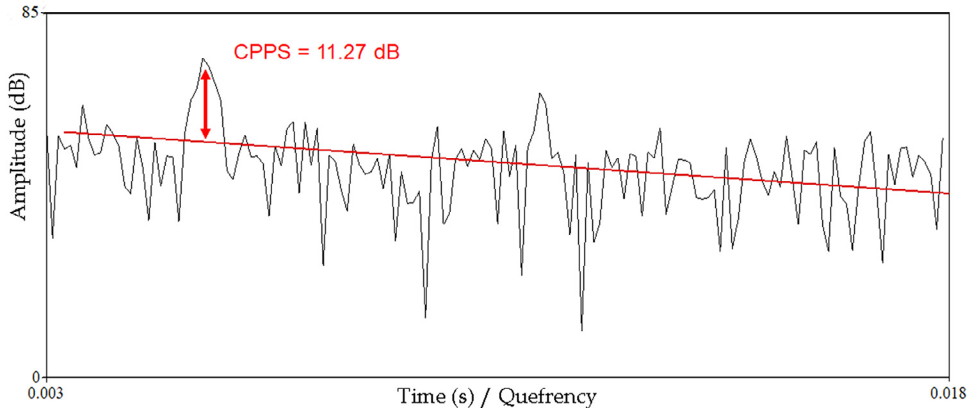

FIGURE 1. Screenshot of a cepstral frame obtained from a sustained vowel sample using Praat. The distance between the highest peak and the corresponding point on the regression line below equals 11.27 dB. Thus, CPPS=11.27 dB.

compared with the pre-perturbation window ($P < 0.001$). Regression estimates for the other loudness-shift conditions indicate how much CPPS_DIFF for each loudness-shift variable compared to CPPS_DIFF for the control trials (ie, the model intercept). In trials with loudness-shifts, CPPS significantly changed compared to control trials for all conditions except for following responses to −3 dB loudness-shifts. Fig. 2A and Fig. 2B display the raw mean CPPS values (as opposed to the CPPS_DIFF values) for the preperturbation and postperturbation windows for each condition. In terms of response direction, in Fig. 2A, upward loudness responses to loudness-shifts resulted in an increase in CPPS and a significant difference from control trials (ie, opposing a downward shift or following an upward shift). Downward loudness responses to loudness-shifts in Fig. 2B resulted in a significant change in CPPS compared to control trials except for following responses to −3 dB loudness-shifts.

Table 2 displays the model output for a linear mixed effects regression model with CPPS_DIFF as the dependent variable, pitch-shift magnitude and response direction as the fixed effects, and a random intercept by participant. Similar to the first model, the regression estimate for the intercept displays CPPS_DIFF for control trials, or how much CPPS values changed between two measurement windows without feedback shifts present. There was a significant effect for the model intercept (ie, the control trials), indicating that in the presence of no pitch-shift, CPPS decreased by 0.15 dB (SE = 0.05) in the postperturbation window compared with the preperturbation window ($P < 0.01$). Regression estimates for the other conditions indicate how much CPPS_DIFF for each pitch-shift variable compared to CPPS_DIFF for the control trials (ie, the model intercept). Trials with opposing pitch-shift responses to −50 cent and −100 cent pitch-shifts resulted in an increase in CPPS by 0.11 dB (SE = 0.09), which was a 0.25 dB (SE = 0.09) difference from control trials ($P < 0.01$). Trials with following responses to +50 cent and +100 cent pitch-shifts resulted in a 0.01 dB (SE = 0.09) increase in CPPS, which was 0.15 dB (SE = 0.09) different from control trials (n.s., $P > 0.05$). Lastly, trials with opposing responses to +100 cent pitch-shifts resulted in a 0.37 dB (SE = 0.09) decrease in CPPS, which was a −0.23 dB (SE = 0.09) difference from control trials ($P < 0.05$). Fig. 3A and Fig. 3B show the raw mean CPPS values for upward (Fig. 3A) and

TABLE 1.
Estimated Regression Parameters, Standard Errors, Degrees of Freedom, and *t* Values for the Linear Mixed Effects Regression Model for Loudness Perturbations

Response Direction	Loudness-Shift Magnitude	CPPS_DIFF Estimate	St. Error	*df*	*t*	*P*
Control	0 dB	**−0.24**	**0.04**	**86.27**	**−5.47**	**<0.001**
Opposing	−3 dB	**0.30**	**0.08**	**4,469.18**	**3.58**	**0.00**
	+3 dB	**0.28**	**0.08**	**4,467.53**	**3.16**	**0.00**
	−6 dB	**0.26**	**0.08**	**4,464.86**	**3.29**	**0.00**
	+6 dB	**0.22**	**0.09**	**4,462.34**	**2.49**	**0.01**
Following	−3 dB	0.01	0.09	4,447.80	0.10	0.94
	+3 dB	**0.51**	**0.08**	**4,469.34**	**6.33**	**<0.001**
	−6 dB	**0.20**	**0.08**	**4,464.90**	**2.34**	**<0.001**
	+6 dB	**0.39**	**0.08**	**4,470.27**	**4.88**	**0.02**

The estimated regression parameters refer to the difference in CPPS-DIFF from control trials (first row in the table).

TABLE 2.
Estimated Regression Parameters, Standard Errors, Degrees of Freedom, and t Values for the Linear Mixed Effects Regression Model for Change in CPPS for Pitch-Shifts

Response Direction	Pitch-Shift Magnitude	CPPS_DIFF Estimate	St. Error	*df*	*t*	*P*
Control	0 Cents	**−0.15**	**0.05**	**92.91**	**−2.95**	**0.00**
Opposing	−50 Cents	**0.25**	**0.09**	**4,277.00**	**2.72**	**0.01**
	+50 Cents	−0.17	0.11	4,285.78	−1.57	
	−100 Cents	**0.25**	**0.09**	**4,283.57**	**2.71**	**0.01**
	+100 Cents	**−0.23**	**0.11**	**4,288.35**	**−2.14**	**0.03**
Following	−50 Cents	−0.06	0.09	4,278.56	−0.69	
	+50 Cents	0.15	0.08	4,279.71	1.87	
	−100 Cents	−0.02	0.09	4,278.95	−0.26	
	+100 Cents	0.15	0.08	4,279.71	1.85	

The estimated regression parameters refer to the difference in CPPS-DIFF from control trials

downward (Fig. 3B) f_o responses to pitch-shifts. In trials with pitch-shifts, CPPS only increased from the pre- to post-perturbation windows when there was an upward f_o response to pitch-shifts. Fig. 3B shows changes in CPPS when there was a downward f_o response to pitch shifts.

DISCUSSION

In this study, we used loudness-shift and pitch-shift paradigms in sustained vowel production to measure the change in CPPS pre- and post-perturbation. We were interested in whether correction of loudness and pitch through auditory feedback control affects vocal quality, and, more specifically, whether loudness-shifts or pitch-shifts affect vocal harmonicity differently. We predicted that changes in auditory feedback overall would affect vocal quality but that changes in loudness, in particular, would affect vocal quality more than changes in pitch because previous studies[15,21] have established a clear relationship between loudness and CPPS values, whereas the relationship between CPPS and pitch is less clear. Information about the underlying auditory-motor mechanisms that control voice quality may be inferred where results diverged from these expectations.

Perceptual salience

Changes in CPPS measured in the present study were small, and it is relevant to include a discussion of the perceptual

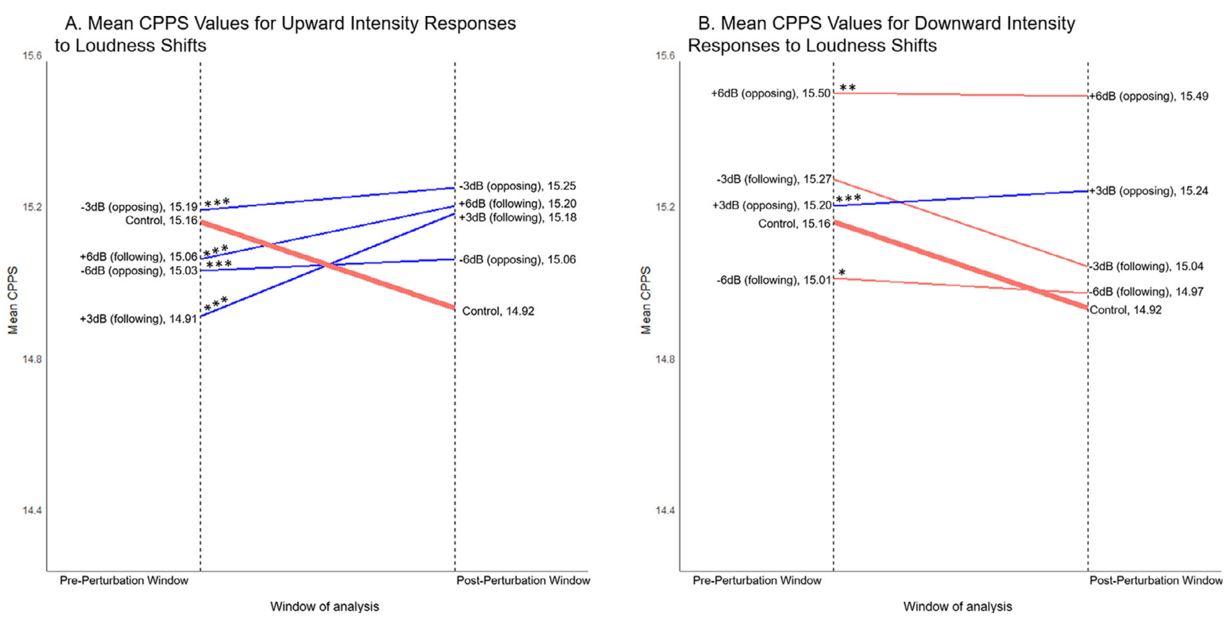

FIGURE 2. A and B: Comparison of mean CPPS values between the pre-perturbation window and the post-perturbation window. The blue and red lines indicate the slope of change from the pre-perturbation window (left-hand column) to the post-perturbation window (right-hand column). Positive changes are indicated by blue lines and negative changes are indicated by red lines. Control trials are represented by a thickened line compared to the trials with pitch-shifts. Fig. 2A displays trials with upward intensity responses to loudness shifts and Fig. 2B displays trials with downward intensity responses to loudness shifts. Statistical significance (indicated by stars) is defined as whether there was a significant difference in slope of change in CPPS between the trials with loudness-shifts to the control trials.

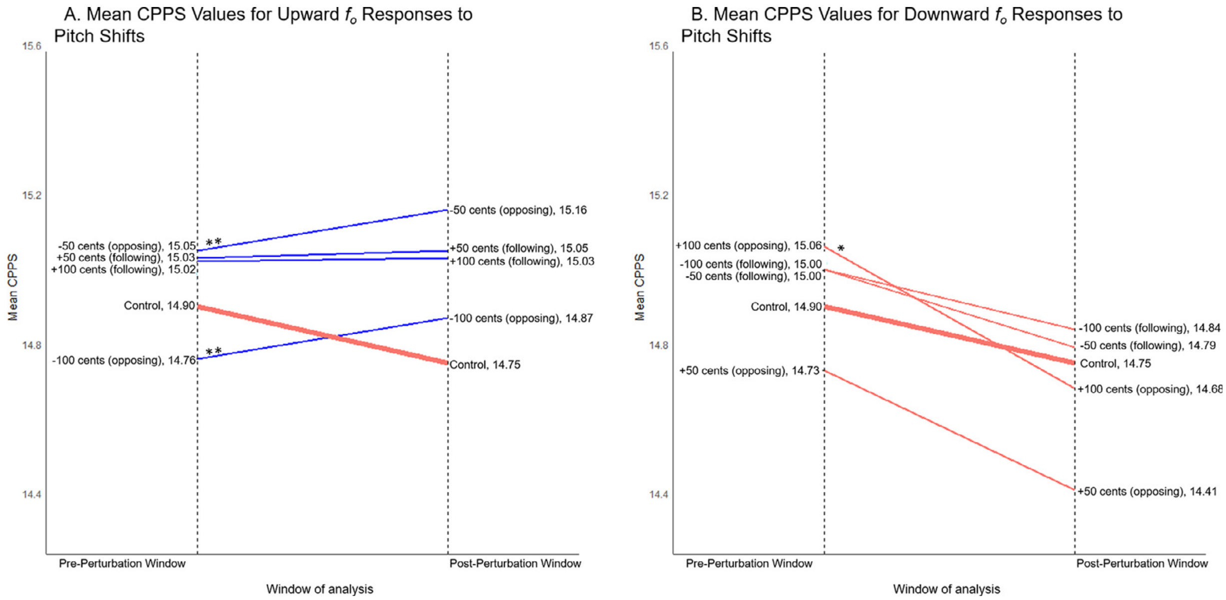

FIGURE 3. A and B: Comparison of the mean CPPS values between the pre-perturbation window and the post-perturbation window. The blue and red lines indicate the slope of change from the pre-perturbation window (left hand column) to the post-perturbation window (right-hand column). Positive changes are indicated by blue lines and negative changes are indicated by red lines. Control trials are represented by a thickened line compared to the trials with pitch-shifts. Fig. 3A displays trials with upward fo responses to pitch shifts and Fig. 3B displays trials with downward fo responses to pitch shifts. Statistical significance (indicated by stars) is defined as whether there was a significant difference in the slope of change in CPPS between the trials with pitch-shifts to the control trials.

salience of our results. Although CPPS is highly correlated with listener ratings of voice samples, it is a measure of the harmonicity of the signal and not a direct indication of the auditory-perceptual features of voice quality. The Consensus Auditory- Perceptual Evaluation of Voice (CAPE-V) is a 100 mm visual analog scale to assess six quality features of voice: overall severity, roughness, breathiness, strain, pitch, and loudness.[1,46] A recent study[46] provided a useful framework to relate CPPS values to overall voice severity in the CAPE-V using a regression formula (−7.31*CPPS + 115.34= Mean Listener Rating of Overall Severity).[46] This linear regression model was constructed for /a/ vowels analyzed in Praat using the algorithm described by Maryn and Weenink,[40] which was identical to the protocol used in the present study. Therefore, we deemed it appropriate to use this formula to indicate the perceptual salience of the small changes in CPPS in our results. For significant results, the mean change in listener rating for vocal responses to loudness-shift results was 0.43 mm with a standard deviation of 0.64, and for pitch-shift results, -0.33 mm with a standard deviation of 1.73. The largest change was approximately 2 mm on the 100 mm CAPE-V scale, suggesting that our results had minimal perceptual salience for overall voice severity. However, because the regression formula only related CPPS values to overall severity ratings, it is unclear how these measurements would differ when compared with other voice quality features such as roughness or breathiness. The subjects in the present study were not dysphonic, thus an overall severity rating might not be appropriate to capture a listener's perception of subtle but audible voice quality changes across a sustained vowel.

Control trials

An initial finding was that CPPS significantly decreased in the absence of auditory feedback shifts. In other words, for any 600-ms segment measured in a 6-second sustained vowel, harmonicity was reduced between the first half of the segment compared to the last half of the segment. This trend was seen consistently across participants and cannot be fully accounted for by random variations in voice quality across a sustained vowel. Few studies have examined how measures of CPPS vary over a single vowel, likely because this measure is derived from the quefrency-domain rather than from the time-domain. A recent study examined the effects of vowel duration on CPPS and found that, on average, vowels with a longer duration result in lower CPPS values than vowels with a shorter duration in a sustained-vowel task.[21] The authors suggested that these results were in part due to shorter vowel segments containing less information regarding signal periodicity and harmonicity than longer segments. The results of our study suggest that CPPS may be reduced across longer vowels over time, potentially due to loss of subglottal pressure and reduced vocal intensity. Further studies are needed to explore the relationship between vowel duration and CPPS over time.

Loudness-shifts

Regarding the effect of loudness-shifts, when both upward and downward loudness-shifts were applied during vowel production, there was less of a decrease in CPPS than in control trials overall, and for some conditions, there was an increase in CPPS. CPPS significantly decreased in control trials when no perturbations were present, indicating that harmonicity is naturally reduced across production. Unexpected loudness-shifts in auditory feedback slowed this reduction in CPPS, resulting in more harmonicity being retained in the voice signal. Interestingly, some loudness-shifts resulted in an increase in CPPS while some simply reduced the negative slope, and this effect was largely driven by response direction. When a loudness-shift resulted in an increase in voice loudness (eg, opposing a downward perturbation or following an upward perturbation), CPPS also increased after the shift. This finding suggests that a change in auditory feedback that results in louder voicing improves vocal harmonicity. A potential explanation is that the louder voicing increases vocal fold contact and respiratory pressure causing an increase in vibrational periodicity and vocal harmonicity. This finding implies that auditory feedback manipulations that trigger louder vocal responses can improve vocal harmonicity and, thus, vocal quality.

Loudness-shifts that resulted in a decrease in vocal loudness (eg, opposing an upward perturbation or following a downward perturbation) overall reduced the negative slope of change for CPPS. Opposing responses to +6 dB shifts and following responses to −6 dB shifts both resulted in a decrease in CPPS, however, the negative slope was significantly less than control trials. A different trend was observed for opposing responses to +3 dB shifts, which resulted in a positive increase in CPPS even though the vocal response decreased in loudness. Overall, these findings suggest that the presence of loudness-shifts of any shift direction or response direction improve vocal harmonicity compared to control trials. Interestingly, +3 dB shifts appear to have a strong effect on harmonicity. Both opposing and following responses to +3 dB shifts resulted in increased CPPS, and following responses to +3 dB shifts, specifically, had the largest effect across conditions. There is a possible explanation for this surprising result. In Bauer et al,[12] response gain (response magnitude/shift magnitude) was greater for smaller loudness-shifts.[12] This result suggests that the audio-vocal system for voice amplitude regulation is more efficient for responding to smaller errors in vocal loudness. In relation to our current study, it is possible that this effect generalizes to vocal harmonicity such that the audio-vocal system for voice harmonicity regulation is more efficient for correcting for smaller errors across vocal parameters. Furthermore, it is possible that −3 dB shifts did not produce as large of a response as +3 dB shifts because the quieter −3 dB perturbation was not as easily perceived. An increase in voice loudness may be more noticeable, and thus generate a larger response.[12] Additionally, Liu et al[47] demonstrated directional effects of larger vocal response magnitudes to downward pitch shifts. It is possible that differential responses to upward and downward shifted loudness feedback in the present study could be due to similar directional effects. A potential implication from this work is that small increases in voice loudness feedback may be particularly beneficial for improving vocal quality.

Pitch-shifts

While loudness-shifts had a robust effect on CPPS, the presence of pitch-shifts had an inconsistent and minimal effect. Change in CPPS only differed significantly from control trials for three conditions: opposing responses to −50 cents shifts, −100 cents shifts, and +100 cents. While the first two conditions (opposing responses to −50 and −100 cent shifts) significantly increased CPPS compared to control trials, the latter condition (+ 100 cents) significantly decreased CPPS compared to control trials. This pattern of findings can be explained by looking at response direction. Opposing responses to downward pitch shifts, by definition, result in pitch increases. Sampaio et al[21] established an increasing trend in CPPS relative to increasing pitch. Participants in the current study may have used increased loudness and muscular force when ascending in pitch, leading to increased medial compression of the vocal folds and slightly higher measures of CPPS.[15,21] On the contrary, when responses opposed +100 cent shifts, they decreased in pitch. This lowering in pitch decreased CPPS and thus vocal quality, possibly due to a reduction in the medial compression of the vocal folds as participants lowered their pitch. While our finding provides evidence that downward pitch-shift responses can result in decreased CPPS, this pattern was not observed across all downward responses. Apart from opposing responses to +100 cent shifts, there were no significant differences in change in CPPS for any other condition that resulted in a downward response. It is possible that lowering the pitch within these ranges does not require a change in muscular force that would significantly affect glottal adduction and thus vocal harmonicity.

Improved audibility

Results from the present study suggest that vocal quality is affected by unexpected alterations in loudness and pitch auditory feedback, but more-so by changes in loudness auditory feedback. CPPS values were consistent with expectations established in previous studies that intensity and f_o patterns are directly related to CPPS.[15,21] However, in the present study, loudness-shifts with downward responses (ie, reduced loudness) caused less of a decrease in CPPS compared to control trials. Under normal conditions, quieter voicing would be expected to cause a sharper decrease in CPPS than normal voicing. Thus, the known physiological mechanisms of voice production responsible for the relationship between CPPS measures and loudness in normal voicing conditions do not fully explain the results in the present study.

One of the earliest discoveries regarding the importance of auditory feedback and voice production is the Lombard effect which describes a phenomenon where speakers tend to raise their vocal intensity in the presence of environmental noise to make themselves audible.[33,48] Additionally, speaking in noise tends to increase articulatory precision and acoustic measures of prosody showing emphasis on important words, both of which act to improve a speaker's overall intelligibility.[49−51] Although the loudness-shift reflex is produced under altered auditory feedback conditions, not background noise, there may be a similar mechanism of control for voice quality; a clearer voice signal is produced in the presence of loudness feedback perturbations which may act to increase a speaker's intelligibility/audibility. Although this is a conceivable interpretation of the results, future studies should aim at identifying the underlying mechanisms involved in the effect of auditory feedback on control of voice quality.

Implications for voice disorders

Thus far, we have discussed how loudness-shifts had a greater effect on CPPS than pitch-shifts and how this may be related to a mechanism for improving audibility under altered auditory feedback conditions. These findings have potential implications for dysphonia and related voice disorders. A common aim of speech-language pathologists in the treatment of voice disorders is to improve voice quality.[2,52] Because of the relevance of auditory feedback in voice control, many voice therapy models involve drawing attention to a patient's perception of auditory feedback to help establish production and awareness of new voice use patterns and to promote generalization and maintenance of these behaviors.[5,52] Additionally, masking noise and the Lombard effect are used in voice therapy to improve vocal loudness in patients with Parkinson's disease who often present with low amplitude voicing and articulatory undershoot.[53−55] The Lombard effect has also been used in cases of functional aphonia/dysphonia by using masking noise to reduce the patient's ability to hear their vocal output, thus helping them to initiate phonation or to produce voice at an increased loudness.[56,57] Although manipulated and heightened auditory feedback have been useful clinical tools, given the ample evidence in scientific research regarding the influence of auditory feedback on voice control, there may be a broader range of applications of auditory feedback manipulation in the clinical setting.

The use of altered auditory feedback in voice therapy has mostly centered around the goal of increasing vocal loudness, however, masking noise may also result in improved voice quality in healthy subjects.[51,52,58,59] Pending further investigation, auditory feedback manipulation may have potential therapeutic value in a range of voice disorders which affect voice quality. Increased loudness due to the Lombard effect may be contraindicated in patients with phonotraumatic lesions because of the contribution that increased vocal fold contact in louder phonation may have to fibrovascular changes of the vocal folds.[60] Excessive loudness demands and inappropriate intensity are also correlated with vocal hyperfunction, a primary feature of muscle tension dysphonia.[61,62] This factor may negate some of the usefulness of masking noise in these populations due to its primary effect of increased loudness. However, the results of the present study suggest that all loudness perturbations, even those resulting in decreased vocal intensity, result in an increase in voice harmonicity and thus, an improvement in vocal quality. This implies that loudness-shifted feedback could be used to improve voice quality without increasing voice loudness in patients with phonotraumatic lesions or muscle tension dysphonia. However, further research is needed to determine the underlying physiological changes that alter voice quality in the presence of loudness-shifts and to rule out maladaptive compensatory strategies. Additionally, this interpretation requires testing in a patient population before it is applied therapeutically.

Limitations

Although this study produced compelling results, several limitations should be discussed. First, the sustained-vowel task only included /a/ vowels, and results may not generalize to other vowel types. Previous studies suggest that vowel type has a significant effect on CPP.[15,21] Therefore, research on the effects of loudness-shifted and pitch-shifted feedback on vocal quality should be expanded to include /i/ and /u/ vowels. Second, the experimental procedure utilized both loudness-shifts and pitch-shifts in alternating blocks. Although this has not been tested, it is possible that the participant's vocal responses could have been altered by experiencing both loudness-shifts and pitch-shifts in a single experimental session. Third, changes in CPPS measured in the present study were small and may not be considered perceptually or clinically significant. However, statistically significant trends may provide insight into the relationship between auditory feedback and voice quality control. Fourth, many previous studies have demonstrated the importance of somatosensory feedback in pitch control,[59,63,64] and, although this has not been studied, it is reasonable to predict that somatosensory feedback may also play a role in control of voice loudness. The scope of this study did not include an examination of somatosensory feedback or its possible interactions with auditory feedback for control of voice quality. Given the emphasis of somatosensation in many prominent voice therapy protocols,[5,65,66] future studies should aim to explore its role in control of voice quality. Fifth, the experimental procedure utilized relatively small pitch and loudness perturbation magnitudes ($\pm$0, 3, and 6 dB, or $\pm$0, 50, and 100 cents). It is possible that larger perturbations would have produced more of a change in CPPS, especially in pitch-shifted conditions. Sixth, our postperturbation window included the 200 ms perturbation to ensure that the reflexive vocal response, which has been shown to have a short latency period,[8] was captured in our window of analysis. Due to the novelty of our design, it is unknown how this window of analysis might affect our results. It is possible that excluding the perturbation from the analysis would significantly alter our results, and alternative methods of segment selection should be considered for future studies. Seventh, the target voice loudness output range in this study was 73-75 dB SPL at a 2.5-centimeter distance from the corner of the mouth, which was a perceptually soft voice. It is possible that the effects demonstrated in the present study would not be generalizable to a louder voice. Lastly, the sample in the present study included mainly males (3 females, 22 males). Previous research has indicated that although males and females may have different neurophysiological responses to altered auditory feedback, reflexive vocal responses did not reflect this difference.[67] However, the pattern of muscular activation for pitch changes is likely to differ between males and females because of differences in f_o. Future studies should include a more even ratio of males and females, conduct separate studies for each sex, and compare differences.

CONCLUSION

Overall, results from the present study suggest that vocal quality (as measured by CPPS) was significantly affected by unexpected alterations in loudness auditory feedback, whereas pitch alterations had inconsistent and minimal effects. In the absence of perturbations, CPPS significantly decreased, suggesting that CPPS may be reduced across longer duration vowels over time. Both upward and downward loudness-shifts caused less of a decrease in CPPS than in control trials overall, and for some conditions, there was an increase in CPPS; +3 dB shifts resulted in a positive increase in CPPS even when the vocal response decreased in loudness. Regarding pitch-shifts, significant change in CPPS was only observed in three conditions: opposing responses to −50 cents shifts and −100 cents shifts (significant increase in CPPS), and +100 cents (significant decrease in CPPS). Most of the resultant CPPS values were consistent with expectations based on physiological changes required to alter pitch and loudness. However, we observed that loudness perturbations with downward responses (ie, reduced loudness) caused less of a decrease in CPPS compared to control trials than we would expect to see in normal voicing. We propose that there may be a mechanism of control for voice quality that acts to increase harmonicity of the voice signal to improve voice audibility in the presence of loudness auditory feedback perturbations.

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