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Effects of Masking Noise on Laryngeal Resistance for Breathy, Normal, and Pressed Voice

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Purpose: The purpose of the present study was to explore the effects of masking noise on laryngeal resistance for breathy, normal, and pressed voice in vocally trained women.
Method: Eighteen vocally trained women produced breathy, normal, and pressed voice across 7 fundamental frequencies during a repeated CV utterance of /pi/ under normal and masked auditory feedback. Dependent variables were mean and standard deviation of laryngeal resistance (LR; cmH_2O/l/s).
Results: LR values for breathy and normal voice remained constant across normal and masked auditory feedback, whereas LR values for pressed voice increased significantly from normal to masked auditory feedback.
Conclusions: The results suggest that both voice pattern and feedback condition influenced the stability of the LR data. Specifically, the pressed voice pattern may be more susceptible to auditory feedback influence because it was less stable than the breathy and the normal voice patterns. Future investigation should continue to explore the relevance of auditory feedback for theoretical and clinical issues surrounding voice.

KEY WORDS: voice, auditory feedback, masking noise, laryngeal resistance, breathy, normal, pressed

It is generally acknowledged that auditory feedback is important for the control of voice related to speech and singing. Consequently, the role of auditory feedback on voice control has been studied using different experimental approaches including induction of the Lombard effect, side-tone amplification (as cited in Lane & Tranel, 1971), masking noise (Elliott & Niemoeller, 1970; Ward & Burns, 1978), and perturbation (Elman, 1981). Lombard investigated the role of voice amplitude control in the presence of environmental noise. The *Lombard effect* is demonstrated when masking noise causes an automatic increase in voice amplitude to a level that exceeds the noise level and thus enables a speaker to be heard (as cited in Lane & Tranel, 1971). A related phenomenon is *side-tone amplification*. In side-tone amplification, speakers produce an increase in voice amplitude when they perceive that their voice is too quiet and a decrease in voice amplitude when they perceive that their voice is too loud. Thus, speakers modulate voice amplitude to compensate for changes in the loudness of voice auditory feedback (as cited in Lane & Tranel, 1971).

In *masking noise studies,* researchers use noise to block auditory feedback. Several studies demonstrated that the presence of white noise impaired the ability of normal speakers and trained singers to control voice F_0 (Elliott & Niemoeller, 1970; Gammon, Smith, Daniloff, & Kim, 1971; Mürbe, Pabst, Hofmann, & Sundberg, 2002; Ternström, Sundberg, & Collden, 1988; Ward & Burns, 1978). A follow-up study investigating the effects of 3 years of singing training on pitch control in the presence of masking noise found that pitch accuracy tended to improve in slow singing, but no improvement was noted in fast singing (Mürbe, Pabst, Hofmann, & Sundberg, 2004).

In *perturbation studies,* the primary goal is to disrupt auditory feedback and not eliminate it to better understand voice motor control. Elman (1981) proposed a perturbation paradigm in which the participant's voice is unexpectedly shifted in frequency either up or down by an external device and fed back to the participant instantaneously over headphones. Many participants respond to this pitch-shifting technique by changing F_0 (Elman, 1981). Most of the recent studies related to the role of auditory feedback on voice control for F_0 and amplitude have used Elman's basic method for perturbation. For voice control of F_0, participants have tended to demonstrate a "compensatory" response in the opposite direction of the pitch-shifted feedback in approximately 80%–90% of trials. For example, when the pitch-shifted feedback increased, the participant's F_0 decreased, and conversely when the pitch-shifted feedback decreased, the participant's F_0 increased. The compensatory response might suggest that the participants are attempting to retain what they perceive as stable F_0 by compensating in the opposite direction of the auditory feedback. Interestingly, in approximately 10%–20% of trials, participants have demonstrated a "following" response in the same direction as the pitch-shifted feedback. That is, participants produced an increase in F_0 in response to an upward perturbation in pitch-shifted feedback, and participants produced a decrease in F_0 in response to a downward perturbation in pitch-shifted feedback. The following response might suggest that the participants misperceive the perturbation of the acoustic system and alter F_0 in the same direction as the perturbation. Such responses have been observed during sustained vowels, glissandos, speech, and singing (Burnett, Freedland, Larson, & Hain, 1998; Burnett, Senner, & Larson, 1997; Chen, Liu, Xu, & Larson, 2007; Leydon, Bauer, & Larson, 2003; Sivasankar, Bauer, Babu, & Larson, 2005; Xu, Larson, Bauer, & Hain, 2004). For control of vocal amplitude, it has also been demonstrated that perturbation of voice loudness feedback results in both compensatory and following responses (Bauer, Mittal, Larson, & Hain, 2006; Heinks-Maldonado & Houde, 2005).

Thus, research related to F_0 and amplitude control suggests that pitch and loudness perturbations elicit similar responses. To explore the control mechanisms underlying the similar behavioral observations, Larson, Sun, and Hain (2007) studied whether control mechanisms for voice F_0 and amplitude are independent. Their results showed that the basic properties of F_0 and amplitude responses to stimuli are similar, which led the authors to suggest that the two share a common neural circuitry. The results of their study, however, in which both F_0 and amplitude perturbations were presented simultaneously, demonstrated that the two systems can respond largely independent of each other with small nonlinear interactions. Thus, overall it appears that the two mechanisms for F_0 and amplitude control in human voice are predominantly independent, but share some circuitry and interact to a minor extent (Larson et al., 2007).

In summary, the study of auditory feedback influences on voice control has primarily focused on F_0 and amplitude by manipulations in masking noise and in pitch-shifted or amplitude-shifted perturbations. Two of the earliest effects demonstrated were the Lombard effect and side-tone amplification. The Lombard effect represents changes in voice amplitude in response to environmental noise, whereas side-tone amplification represents changes in voice amplitude in response to loudness of voice auditory feedback. Masking noise procedures have demonstrated instability of F_0 in normal speakers and trained singers. Perturbations of pitch and amplitude feedback facilitate changes in voice F_0 and amplitude. The mechanisms that underlie control for F_0 and amplitude may be independent, but share neuronal circuitry and may interact with one another.

Although this body of research has contributed significantly to the understanding of auditory feedback influences on the control of F_0 and amplitude, further work is required to explore auditory feedback influences in the control of different voice patterns that approximate those seen in patients with voice disorders. In the treatment of voice disorders, the speech-language pathologist (SLP) may facilitate the acquisition of a "new" voice pattern indirectly through changes in F_0 and/or amplitude. Currently, however, most SLPs consider voice treatment more globally by directly addressing overall voice production in acquisition of a new voice pattern achieved in therapy. Because auditory feedback is influential in voice control, a large component of voice therapy models should involve the use of auditory feedback to generalize and maintain the new voice in all communication tasks. In fact, a component of the global voice therapy model emphasizes the use of auditory feedback through a unique method involving negative practice (Grillo, 2010). To bring basic science investigations closer to the treatment of voice disorders, more studies are required to assess the influence of auditory feedback on different voice patterns.

What is needed, therefore, is an exploration of auditory feedback influences on clinically relevant voice patterns. Such voice patterns that have been described in the literature as relevant to voice health and function are breathy, normal, and pressed (Alku & Vilkman, 1996; Gauffin & Sundberg, 1989; Grillo, Perta, & Smith, 2009; Grillo & Verdolini, 2008; Sundberg, Titze, & Scherer, 1993). *Breathy voice* involves sharply reduced vocal fold adduction and thus reduced or minimal vocal fold impact stress (Berry et al., 2001; Roy et al., 2003; Verdolini-Marston, Burke, Lessac, Glaze, & Caldwell, 1995). *Normal voice* is characterized by an approximately equal duration of vocal fold adduction and abduction during successive cycles of phonation with intermediate vocal fold impact stress (Alku & Vilman, 1996; Berry et al., 2001; Davis, Bartlett, & Luschei, 1993; Stevens, 1981). *Pressed voice* is thought to be an important etiologic factor in phonotraumatic injury due to tight vocal fold adduction, which increases vocal fold impact stress relative to what are found to be normal values (Berry et al., 2001; Jiang & Titze, 1994).

Of interest for the present research is the concept that voice production operates as a nonlinear dynamic system that involves coordinative interactions among the vocal tract, laryngeal, and respiratory subsystems (Austin & Titze, 1997; Titze, 2002; Titze, Baken, & Herzel, 1993). Consequently, it is reasonable to speculate that motor control for voice—including breathy, normal, and pressed voice—does not target control over separate independent degrees of freedom, but rather targets relations of functions across subsystems in voice production. In that light, contemporary study of these voice types—including studies on the role of auditory feedback—might benefit from using relational measures that distinguish them. In fact, this is the approach taken in the present study. The measure that was selected for study is *laryngeal resistance* (i.e., LR; subglottic pressure divided by average airflow [$cmH_2O/l/s$]; Smitheran & Hixon, 1981), which reflects relations across the respiratory and laryngeal subsystems in voice production. Although LR does not provide a direct indicator of functioning in specific physical units, it is an indirect approximation of passive and active respiratory and laryngeal forces as well as aerodynamic factors in voice production (e.g., Smitheran & Hixon, 1981).

The appropriateness of this measure for the present context was shown in a study by Grillo and Verdolini (2008), which assessed LR's ability to distinguish four different voice patterns. In the study, 13 trained female voice professionals produced five sequential /pi/s across three trials at a production rate of 88 beats per minute in a breathy, normal, resonant, and pressed voice as determined by agreement across the participant and examiner, and later verified by two independent raters. Results showed that LR distinguished all of the voice patterns from one another except normal and resonant. The point for the present discussion is that LR was shown to be a useful relational measure that can distinguish clinically relevant voice types, failing to distinguish only normal and resonant voice. It is likely that the difference between normal and resonant voice patterns does not reside with differences in respiratory–laryngeal relations, but rather with changes in the vocal tract, which are not captured by LR. Based on the results from that study, LR can be considered a valid measure that reflects coordinative voice patterns across respiratory and laryngeal subsystems in voice production.

The purpose of the present study was to explore the effects of masking noise on LR for the clinically relevant voice patterns of breathy, normal, and pressed. The dependent variable was LR ($cmH_2O/l/s$), a coordinative measure reflecting respiratory and laryngeal subsystem interactions in voice production, which our previous work showed reliably distinguished breathy, normal, and pressed voice patterns (Grillo & Verdolini, 2008). Each target voice pattern was produced at a series of F_0s ranging from 220 Hz to 880 Hz to assess any potential effects of masking noise on LR for the voice patterns across a two-octave range. Two auditory feedback conditions were identified, consistent with the masking noise paradigm reported in previous research: normal auditory feedback and masked auditory feedback using speech noise (Elliott & Niemoeller, 1970; Gammon et al., 1971; Mürbe et al., 2002, 2004; Ternström et al., 1988; Ward & Burns, 1978).

The hypothesis was that participants in the present study would demonstrate stable patterns for LR corresponding to breathy and normal voice regardless of F_0 and auditory feedback condition because of their relative ease of production and decreased performance variability as demonstrated in our previous work (see Grillo & Verdolini, 2008). In contrast, LR for pressed voice may not be as stable because of its characteristically effortful phonation pattern requiring intense recruitment of muscle activation and increased performance variability as shown in our previous research (see Grillo & Verdolini, 2008).

Method

Participants

Participants were 18 vocally trained adult women, ages 18–35 years, with a mean age of 20 years. All participants had at least 3 years of choral singing training with no history of private voice lessons. The sample size of 18 participants was based on an anticipated large main effect between the normal auditory feedback and the masked auditory feedback conditions. One rationale for limiting the study to women was to minimize the variability in the data, as voicing characteristics including aerodynamic ones used in the present study may differ sharply across the sexes (Holmberg, Hillman, & Perkell, 1988). In addition, the ability of LR to distinguish breathy, normal, and pressed voice patterns was based on data from vocally trained women (Grillo & Verdolini, 2008). It was unknown if LR would distinguish breathy, normal, and pressed voice patterns across trained and untrained voice users or across sexes.

Participants were in general good health with normal hearing by self-report. They had no current voice disorder by their report and no evidence of voice abnormality on the day of testing, as judged by a licensed SLP specializing in voice disorders. Participants were required to vocally match all of the target F_0s in the present study (i.e., 220 Hz, 277 Hz, 349 Hz, 440 Hz, 554 Hz, 698 Hz, and 880 Hz) as assessed by the experimenter, with a tolerance of about one-quarter tone. In addition, participants enrolled in the study said they felt comfortable producing the target voice patterns over several trials at 880 Hz, the most challenging F_0.

Equipment and Software

The experimental setup is presented in Figure 1. Aerodynamic data were captured using a Rothenberg (1977) circumferentially vented face mask manufactured by Glottal Enterprises with attached airflow (Model No. 1-in. D-4V) and pressure (Model No. 10-in. D-4V) transducers manufactured by All Sensors. A lavalier microphone (Audio-Technica) was inserted and secured by a plastic stopper into the open end of the face mask to record F_0 and intensity. The microphone communicated with a Compaq Presario R3000 laptop computer via a Sound Blaster Audigy 2 ZS sound card with 24-bit/96-kHz inputs and ASIO 2.0 support for recording and high-fidelity 104 dB signal-to-noise ratio. The microphone was adequate for F_0 extraction from the recorded signal. The pressure and flow transducers communicated via the data translation device (Data Translation BNC Box USB 9800 series) to the laptop computer with a software program that ran the experiment. A Casio CTK-491 keyboard was used to provide a specific target pitch before each trial. A metronome was used to provide the beat pattern (88 beats per minute) for production of CV strings (/pi/). Attached to the laptop running the experiment was a Dell flat screen monitor that provided online feedback of F_0 and intensity to the participants. The software program that ran all aspects of the experiment, including calibration, data collection, online feedback, and data analysis, was designed by an engineering consultant (Neil Szuminsky).

Figure 1. Experimental setup.

Low-pass filtered speech noise was used for the masked auditory feedback condition. The speech noise was delivered by a GSI clinical audiometer manufactured by WelchAllyn via Optimus Pro-155 stereo supra-aural headphones at an intensity of 95 dB SPL. As determined during piloting of the experimental setup, the intensity level of the speech noise masker was effective in masking voice without causing discomfort to the participants. The speech noise was low-pass filtered and was equivalent to the standardized noise typically used for masking speech (International Electrotechnical Commission, 1979). In brief, low-pass filtered speech noise effectively masks bone conduction because bone conduction predominantly transmits low frequencies. There was no simple way of physically measuring the effectiveness of bone conduction; therefore, the experimenter relied on the participants' observations as to whether they could hear their voice productions. In addition, large, cuplike supra-aural headphones were used to minimize transmission of the air-conducted signal.

The software program that ran the experiment featured a calibration function and an experiment function. The airflow measurement equipment was calibrated for aerodynamic functions prior to each day's data collection using a Micro Tronics U tube manometer for pressure and a Glottal Enterprises pneumotach calibration unit for airflow. Acoustic calibration was completed before data collection began using a sound-level calibrator (General Radio Company Type 1562A) for F_0 and intensity. The dB SPL values were measured after procedures described by Baken (1996). The dB SPL values were calculated using the reference SPL from the sound-level calibrator at 500 Hz. Acoustic calibration of the microphone was set at 114 dB SPL considering the close proximity of the microphone to the participants' mouth. The software calculated dB SPL of the signal as 20 times log base of 10 (square of root-mean-square [RMS] of voice divided by square of RMS of reference). This provided change from reference (0 dB being no change); assuming reference was the calibrated signal of 114 dB SPL from the sound-level calibrator. The function of the software program was to guide the experiment's timing; provide participants online feedback of F_0 and intensity; and calculate LR, F_0, and intensity for use in later data analysis.

Procedure

After informed consent, participants completed screening procedures. For screening, participants answered questions pertaining to age, years and type of vocal training, and hearing acuity. In addition, participants vocally matched pitches while sustaining an /a/ for 2 s across the seven target F_0s, so their pitch-matching abilities could be assessed. Eighteen potential participants completed screening procedures, and all were enrolled in the study because they met the inclusion criteria, which included vocally healthy women between the ages of 18–35, at least 3 years of choral singing training with no history of private voice lessons, self-report of normal hearing, and the ability to vocally match all seven target F_0s.

After passing the screening, participants were oriented to the voice patterns and the target utterance for approximately 5 min. Specifically, participants were introduced to breathy, normal, and pressed voice by way of a brief verbal description and demonstration by the experimenter on the vowel /i/; this procedure was based on published descriptions of the voice types (Peterson, Verdolini-Marston, Barkmeier, & Hoffman, 1994) and extensive personal experience. Briefly, pressed voice was demonstrated and described as an extremely high-effort phonation mode with the perception of an almost completely closed airway, as if pushing. Normal voice was demonstrated and described as a spontaneous voicing mode without any attempts to manipulate usual voice production. Breathy voice was demonstrated and described as easy phonation characterized by auditory air escapage during phonation with the vocal folds more apart than closed. Participants were then asked to practice the voice patterns on the /i/ vowel and then on the target CV syllable string /pi pi pi pi pi/ at 277 Hz and at 554 Hz. Although participants had been provided with exemplars of each of the voice patterns, participants were instructed to produce their own versions of the patterns for each utterance. Participants were then oriented to other aspects of the task. They were trained to place a vented mask over their mouth and nose, while positioning plastic tubing intraorally connected to the pressure transducer, avoiding blockage of the tube by the tongue. A strap was placed around the participant's head and tightened to secure a tight seal with the participant's face. After the experimenter checked the mask positioning to verify the seal, the participant was trained to produce a five-syllable CV syllable string (/pi pi pi pi pi/) at an approximate rate of 88 beats per minute (Holmberg et al., 1988).

When participants were finished being oriented to the task, they proceeded to experimental conditions that involved repeated /pi pi pi pi pi/ productions using each of the three voice patterns across F_0 and feedback conditions. Each experimental condition involved three /pi pi pi pi pi/ sequences. Each of the three repetitions was separated by a 1-s rest for a total time of 12 s–13 s for a complete trial of three sets. Trials began with an F_0 of 220 Hz and increased in major third increments or four semitone intervals until 880 Hz was achieved for each voice pattern. The F_0 plateaus were 220 Hz, 277 Hz, 349 Hz, 440 Hz, 554 Hz, 698 Hz, and 880 Hz. The first F_0, 220 Hz, was played on the keyboard, and then the participant screen indicated "Go" for the initiation of the trial. After completion of the trial at 220 Hz, the same voice pattern was repeated at 277 Hz and subsequently 349 Hz and so forth until 880 Hz was reached. Participants received a 15-s rest between each F_0 condition, and a 2-min rest before switching to the next voice pattern target. Regarding intensity, the intention was to control output intensity in dB SPL, holding it constant within participants. This procedure was based on initial calibrating trials to identify spontaneous comfortable intensity for each individual (Grillo & Verdolini, 2008).

Participants were encouraged to maintain the target pattern as best as possible throughout all trials. If the voice pattern was not maintained, as determined by the experimenter and/or participant, participants were instructed to recapture it even midtrial (cf. Lee, Blandin, & Proteau, 1996). Voice pattern targets were randomized within and across participants, with the constraint that all participants performed one voice pattern target from 220 Hz to 880 Hz before moving to the next voice pattern target. Participants received online feedback from the computer regarding their ability to satisfy F_0 and intensity criteria. Feedback was presented in the form of a bar graph indicating the F_0 and the intensity level target with the participant's actual production superimposed on the target. During the experiment, participants did not receive computer-generated feedback related to the voice patterns or LR because the performance feedback might have promoted learning, whereas the study targeted issues of motor control.

In addition to the experimental trials just described, participants were also exposed to two feedback conditions: normal auditory feedback and masked auditory feedback. The order of the feedback conditions was randomized within and across participants, with the constraint that all three voice patterns were produced across all seven F_0s in one feedback condition before switching to the second feedback condition. In the normal auditory feedback condition, participants did not wear headphones; therefore, they heard their voice productions with no interference. In the masked auditory feedback condition, participants received speech noise presented to their ears via supra-aural headphones at 95 dB SPL in an effort to block out the ability to hear one's own voice.

Data Reduction

Data reduction involved several steps that were automatized using software designed by Neil Szuminsky. Subglottic pressures were estimated from oral pressures for each trial using software that obtained the interpolated pressure between pressure peaks two and three, three and four, and four and five for each /pi pi pi pi pi/ string, as well as the time-locked average flow for those syllables, F_0, and intensity level (Holmberg et al., 1988). LR (i.e., subglottic pressure divided by average airflow, $cmH_2O/l/s$) was calculated from the combination of the estimated subglottic pressure value and subsequent average airflow value between peaks two and three, three and four, four and five for each /pi pi pi pi pi/ string. Summary files were generated by the software program that indicated standard deviations and means of LR, F_0, and intensity. The standard deviation of LR and mean LR were calculated for each F_0 trial within each auditory feedback condition.

Experimental Design and Statistical Analysis

The experiment used a three-way, within-subject repeated measures design. The three independent variables were (a) voice pattern (i.e., breathy, normal, and pressed), (b) F_0 (i.e., 220 Hz, 277 Hz, 349 Hz, 440 Hz, 554 Hz, 698 Hz, and 880 Hz), and (c) feedback condition (i.e., normal auditory feedback vs. auditory feedback masked by speech noise). The dependent variables were standard deviation of LR ($cmH_2O/l/s$) and mean LR ($cmH_2O/l/s$) within each condition. For experimental trials, the order of voice patterns and feedback conditions were randomly determined within and across participants. For the analyses, univariate procedures were used to address the dependent variables as a function of the independent variables. Specifically, a three-way repeated measures analysis of variance (ANOVA) was conducted on each of the dependent variables, standard deviation of LR, and mean LR. The following assumptions were met for the within-subject repeated measures design: (a) sphericity, (b) normality, and (c) independence by random order of the design. Homogeneity of variance was not tested because of the significant effect of sphericity ($p < .000$) for both dependent variables. Significance level was set at $\alpha = .05$, and post hoc simple main effects were analyzed using the Bonferroni correction.

Results

The results that follow indicate findings for (a) analysis of F_0 and intensity targets, (b) standard deviation of LR, and (c) mean LR.

Analysis of F_0 and Intensity Level Targets

A goal for data collection in the present study was for participants to maintain constant F_0 and intensity throughout all production trials. Information about F_0 and intensity was provided to participants during all productions. Considering a margin of error of one semitone, all targets were met for all pitches. The two highest frequencies (698 Hz and 880 Hz) varied the most under both feedback conditions. For those two targets, the F_0 +/– one semitone was 659.3 Hz–740.0 Hz for 698 Hz and 830.6 Hz–932.3 Hz for 880 Hz. Thus, the two highest frequencies produced by all participants across normal and masked auditory feedback were within a semitone of target (see Table 1).

Regarding results for intensity, a well-known effect is that as F_0 increases, intensity level also tends to increase (Klingholz, 1992; Titze & Sundberg, 1992). In addition, the Lombard effect describes the phenomenon that voice intensity tends to increase under noise conditions and masking (Ferrand, 2006; Garbe, Siegel, & Pick, 1976). In the present study, participants produced utterances over a two-octave F_0 range. The fact that a “comfortable” intensity was established as the target, however, virtually guaranteed that participants would fail to consistently produce that intensity at higher frequencies. In fact, phonetogram data show that both minimum and maximum intensities tend to be considerably larger for high as compared with low F_0s (Klingholz, 1992). A constant mean intensity was not maintained across all seven target pitches under normal and masked auditory feedback for the voice patterns because it was not a reasonable requirement. Requiring maintenance of a constant intensity target in combination with production of the three voice patterns across a two-octave F_0 range was too difficult for the vocally trained participants.

Table 1. Means and standard deviations (*SD*s) of fundamental frequency (F_0; Hz) for each voice pattern at the target seven F_0s under normal auditory feedback and masked auditory feedback.

Target F_0 and feedback	Breathy voice *M* (*SD*)	Normal voice *M* (*SD*)	Pressed voice *M* (*SD*)
Normal feedback			
220	220.88 (4.17)	219.76 (5.18)	221.43 (4.65)
277	277.26 (3.87)	277.96 (3.94)	274.82 (5.80)
349	348.89 (4.77)	347.93 (6.88)	350.08 (4.72)
440	440.39 (6.42)	439.62 (13.21)	438.70 (7.47)
554	554.97 (5.43)	557.06 (4.56)	557.14 (5.95)
698	688.07 (18.24)	696.82 (7.79)	699.11 (7.80)
880	866.64 (16.12)	867.78 (14.39)	856.76 (60.54)
Masked feedback			
220	220.01 (8.39)	224.39 (6.57)	223.29 (12.13)
277	276.05 (10.58)	277.51 (5.71)	275.22 (12.20)
349	347.19 (8.45)	350.11 (5.28)	350.49 (12.05)
440	442.67 (20.84)	437.16 (8.54)	436.97 (10.09)
554	554.77 (13.63)	552.62 (9.03)	548.23 (8.02)
698	683.07 (18.01)	684.76 (12.64)	672.93 (41.95)
880	837.30 (22.05)	843.22 (24.92)	841.36 (42.07)

Even though participants were unable to hold intensity level constant, the mean intensity level appeared to remain consistent across the three voice patterns with a gradual increase in intensity as F_0 increased (see Table 2). In addition, the masked auditory feedback condition generated an increase in intensity level as compared with the normal auditory feedback condition. Pearson correlation coefficients were analyzed to determine if mean intensity influenced mean LR. Forty-two pairs were identified considering two auditory feedback conditions, seven pitches, and three voice patterns. The critical p value was adjusted to account for the 42 tests ($.05/42 = .001, p = .001$). The p values for the 42 correlations, considering two-tailed tests, ranged from .042–.981; therefore, there was no relationship between mean intensity and LR. The results reflected the participants' tendency to increase intensity as pitch increased and also to increase intensity under masking conditions (e.g., Lombard effect). Thus, the changes in intensity level across each of the voice patterns appeared to be related to the increase in F_0 and the specific feedback condition rather than the voice patterns themselves.

Dependent Variable: Standard Deviation of LR

Overall, standard deviation of LR was greater for pressed voice than for either breathy or normal voice, suggesting that pressed voice was not as stable. In addition, standard deviation of LR was higher in the masked auditory feedback condition than in the normal auditory feedback condition. The ANOVA for standard deviation of LR revealed significant main effects for voice pattern, $F(1.03, 17.50) = 6.98$, $p = .016$ (see Figure 2), and feedback, $F(1, 17) = 6.04$, $p = .025$ (see Figure 3). Eta squared, an indicator of effect size, was .291 and .262 for the significant main effects of voice pattern and feedback, respectively. The main effect for F_0, $F(1.79, 30.44) = 0.87$, $p = .419$, and all interactions involving F_0 were not significant, indicating that F_0 did not systematically influence LR variability for the voice patterns. Neither the two-way interaction for Voice Pattern × Feedback, $F(1.07, 18.19) = 3.59$, $p = .072$, nor the three-way interaction for Voice Pattern × F_0 × Feedback, $F(1.59, 27.09) = 0.80$, $p = .433$, was significant. Note, however, that the two-way interaction for Voice Pattern × Feedback approached significance at $p = .072$ with an observed power of .448.

Dependent Variable: Mean LR

Findings for mean LR mirrored those for standard deviation of LR. Overall, the pressed voice pattern was produced with higher mean LR than breathy or normal voice patterns, suggesting that the pressed voice pattern was produced with more resistance to the flow of air. In addition, mean LR was increased in the masked auditory feedback condition as compared with the normal auditory feedback condition. Performance of the voice patterns, therefore, did vary with feedback. Specifically, the pressed voice pattern was produced with increased mean LR in the masked auditory feedback condition, whereas performance of the breathy and the normal voice patterns remained the same across the feedback conditions. The ANOVA for mean LR revealed significant

Table 2. Means and standard deviations (*SD*s) of intensity level (dB SPL) for each voice pattern at the target seven fundamental frequencies (F_0; Hz) under normal auditory feedback and masked auditory feedback.

Target F_0 and feedback	Breathy voice *M* (*SD*)	Normal voice *M* (*SD*)	Pressed voice *M* (*SD*)
Normal feedback			
220	104.40 (2.59)	102.53 (1.86)	99.45 (3.05)
277	105.98 (2.86)	105.53 (1.97)	103.57 (3.07)
349	109.74 (3.63)	112.71 (2.23)	111.20 (2.66)
440	114.24 (3.39)	118.23 (2.02)	117.78 (3.01)
554	119.41 (3.30)	123.58 (2.77)	120.98 (3.44)
698	121.11 (6.02)	127.37 (4.41)	123.44 (3.84)
880	125.82 (7.70)	129.44 (6.12)	124.64 (3.41)
Masked feedback			
220	107.06 (3.55)	108.28 (1.83)	105.35 (3.83)
277	109.53 (3.53)	109.08 (1.82)	107.22 (4.41)
349	113.31 (3.75)	115.86 (2.16)	113.19 (3.23)
440	117.78 (3.97)	116.51 (2.84)	119.55 (3.30)
554	125.81 (3.99)	129.62 (2.85)	123.71 (3.85)
698	131.36 (7.17)	136.74 (3.41)	130.83 (3.18)

Figure 2. Significant main effect for voice pattern, $F(1.03, 17.50) = 6.98$, $p = .016$. Standard deviation of laryngeal resistance (cmH$_2$O/l/s) as a function of voice pattern (i.e., breathy, normal, and pressed).

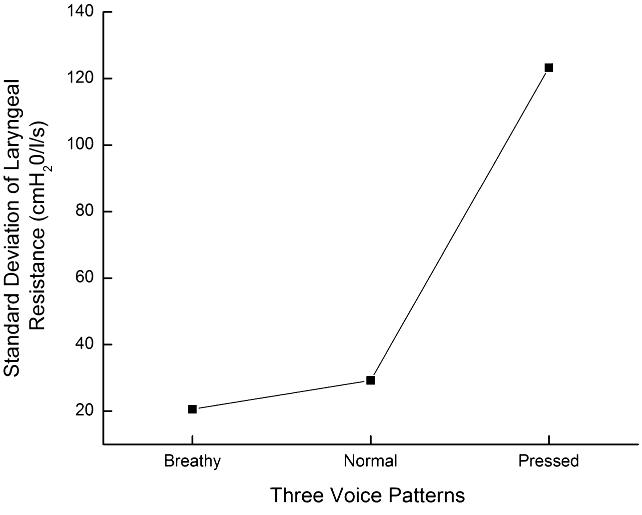


Figure 3. Significant main effect for feedback, $F(1, 17) = 6.04$, $p = .025$. Standard deviation of laryngeal resistance ($cmH_2O/l/s$) as a function of auditory feedback condition (i.e., normal auditory feedback vs. masked auditory feedback by speech noise).

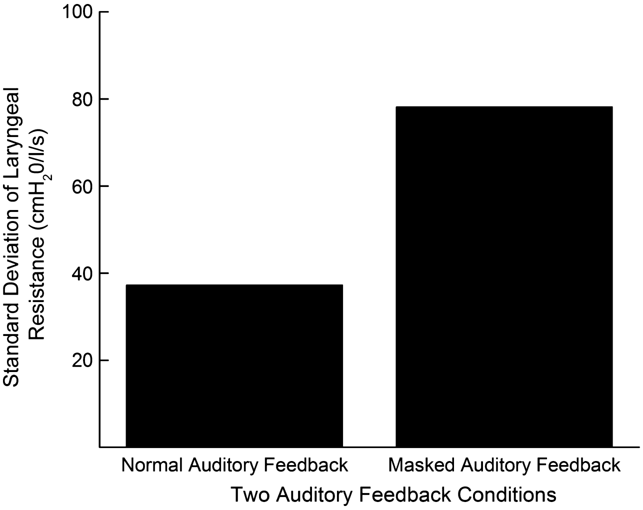
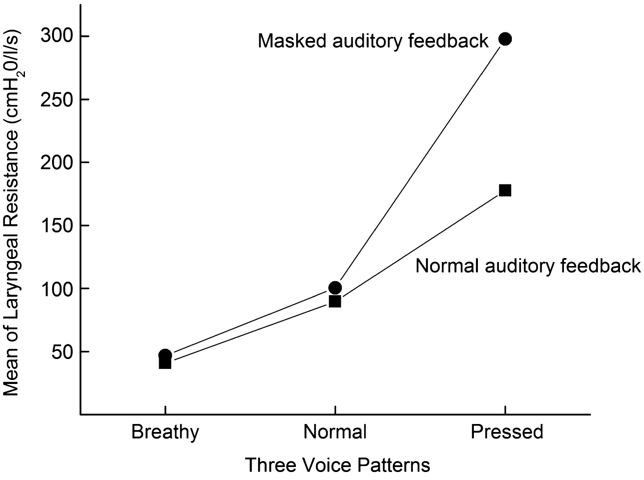


Figure 4. Significant two-way interaction for Voice Pattern × Feedback, $F(1.33, 22.56) = 5.95$, $p = .016$. Mean of laryngeal resistance ($cmH_2O/l/s$) as a function of voice pattern (i.e., breathy, normal, and pressed) for normal and masked auditory feedback.



main effects for voice pattern, $F(1.08, 18.43) = 15.66$, $p = .001$, and feedback, $F(1, 17) = 10.63$, $p = .005$, and a significant two-way interaction for Voice Pattern × Feedback, $F(1.33, 22.56) = 5.95$, $p = .016$ (see Table 3 and Figure 4). Eta squared, an indicator of effect size, was .479 and .385 for the significant main effects of voice pattern and feedback, respectively, and .259 for the significant two-way interaction. Neither the main effect for F_0, $F(2.42, 41.14) = 1.16$, $p = .330$, nor the three-way interaction for Voice Pattern × F_0 × Feedback, $F(2.49, 42.48) = 0.66$, $p = .553$, was significant.

The finding that neither the main effect for F_0 nor any interactions involving F_0 were significant implies that participants maintained the voice patterns regardless of F_0. The significant two-way interaction for Voice Pattern × Feedback indicated that not only did the masked auditory feedback produce elevated mean LR values, but the influence of the masked auditory feedback condition was dependent upon the specific voice pattern. Figure 4 demonstrates that the increase in mean LR was substantially larger for pressed voice in the masked condition, as compared with increases seen in the other voice patterns, for which mean LR increases were trivial. The significant two-way interaction for Voice Pattern × Feedback allowed for further post hoc analysis of simple main effects using the Bonferroni correction. Considering the significant two-way interaction for Voice Pattern × Feedback, nine total pairings were tested. Because nine overall tests were performed, the critical p value was adjusted to account for the nine tests (.05/9 = .005, $p = .005$).

Table 3. Means and standard deviations of laryngeal resistance ($cmH_20/l/s$) for each voice pattern under normal and masked auditory feedback.

Feedback	Breathy voice *M* (*SD*)	Normal voice *M* (*SD*)	Pressed voice *M* (*SD*)
Normal feedback	46.04 (5.20)	83.67 (12.12)	194.63 (37.8)
Masked feedback	54.47 (7.64)	91.58 (15.38)	327.25 (85.94)

For the normal auditory feedback condition, all of the pairwise comparisons between voice patterns were significant: that is, breathy versus normal, $t(35) = 3.05$, $p = .004$; breathy versus pressed, $t(35) = 8.55$, $p < .001$; and pressed versus normal, $t(35) = 5.49$, $p < .001$. The same pattern of results was obtained for the masked auditory feedback condition: that is, breathy versus normal, $t(35) = 3.35$, $p = .001$; breathy versus pressed, $t(35) = 15.66$, $p < .001$; and pressed versus normal, $t(35) = 12.31$, $p < .001$. Participants, therefore, maintained distinctions in mean LR values regardless of feedback condition.

Turning to pairwise comparisons of the voice patterns across feedback condition, for pressed voice, the normal versus masked comparison was significant, $t(35) = 3.51$, $p = .001$. Specifically, pressed voice was produced with larger mean LR values in the masked auditory feedback condition as compared with the normal auditory feedback condition (see Figure 4). In contrast, the normal versus masked pairwise comparisons for breathy, $t(35) = 0.18$, $p = .859$, and normal, $t(35) = 0.32$, $p = .752$, voice were not significant. Thus, feedback condition did not influence mean LR values for either of these patterns.

Discussion

The present study was designed to explore the effects of masking noise on LR for the clinically relevant voice patterns of breathy, normal, and pressed. The results of the study suggest that both feedback condition and voice pattern influenced the stability of LR data. Specifically, pressed voice was produced with increased mean LR in the masked auditory feedback condition as compared with the normal auditory feedback condition, whereas resistance values remained constant for breathy and normal voice across feedback conditions. Pressed voice may be more susceptible to auditory feedback influence because it was more variable than breathy and normal voice. Thus, feedback processes were relevant to performance for some but not all of the voice types. We now turn to a more detailed discussion of the findings.

Standard Deviation of LR

As noted, participants produced pressed voice with the greatest variability (least stability) as compared with breathy and normal voice. Speculatively, increased variability for the pressed voice pattern may have been linked to heightened muscle activation at both glottal and subglottal levels, which in turn influenced the stability of LR. In fact, an increasing linear relationship between amount of force and variability in movement has been noted in the literature for other muscle systems (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). If laryngeal and respiratory systems behave similarly, then such influences could potentially explain the findings. Alternately, aerodynamic factors involving the nonlinear relationship between airflow and pressure at the glottis and subglottis could potentially explain the findings (Austin & Titze, 1997; Titze et al., 1993).

Relative to the effect of feedback on the stability of LR measures, the standard deviation of LR increased under the masked auditory feedback condition. That is, when auditory feedback about participants' performance was effectively eliminated, variability in LR values for the voice patterns increased significantly. Stated differently, auditory feedback was found to influence LR for the voice patterns. Based on previous research that masking noise and perturbation of pitch and amplitude feedback influenced control of F_0 and amplitude (Bauer et al., 2006; Burnett et al., 1997; Elliott & Niemoeller, 1970; Gammon et al., 1971), it is not surprising at all that auditory feedback also played a role in control of LR for the clinically relevant voice patterns in the current study.

Mean LR

Pressed voice was produced with the highest mean LR, whereas breathy voice was produced with the lowest mean LR. Mean LR was intermediate for normal voice, but was closer to values for breathy than for pressed voice. These findings were consistent with those that would be predicted for the respective voice patterns. Pressed voice is typically produced with forcefully adducted vocal folds, both limiting airflow through the glottis and requiring greater subglottal pressure to initiate and maintain vocal fold oscillation. Thus, LR should be high for pressed voice. In contrast, breathy voice is typically produced with a relatively wide glottis. Thus, phonatory airflow through the glottis should be high and pressure backup in the subglottis should be comparatively low. The result would be low values for LR. Regarding normal voice, values for LR should be intermediate because of an intermediate glottal size and, thus, intermediate glottal airflows and subglottal pressures. In summary, mean LR values in the current study were consistent with expectations around the aerodynamic and laryngeal properties of the voice patterns studied.

Conceptually more interesting are findings for mean LR as a function of feedback condition. In both the normal and masked auditory feedback conditions, mean LR was significantly different for all of the voice patterns. Stated differently, all voice patterns were maintained regardless of changing auditory feedback. Even though all voice patterns were distinct from one another within each auditory feedback condition, pressed voice was produced with significantly higher mean LR in the masked auditory feedback condition as compared with the normal auditory feedback condition. Breathy and normal voice were produced with the same mean LR across the normal and masked auditory feedback conditions. The inherent stability of the breathy and normal voice was not affected by the feedback conditions. In contrast, the performance of pressed voice was affected by the masked auditory feedback condition. That is, mean LR for pressed voice increased in the masked auditory feedback condition as compared with the normal auditory feedback condition.

A possible explanation of this finding, that mean LR for pressed voice was influenced by the masking condition, may be related to the increased variability in production of pressed voice as seen in the standard deviation of LR. With the introduction of perturbation to the system through masking noise, the more stable breathy and normal voice patterns were unaffected, but for the more variable pressed voice pattern, participants produced a "more" pressed version as evidenced by the increase in mean LR. Under masking, perhaps the participants relied more on kinesthetic feedback that resulted in production of a more pressed pattern to compensate for the lack of auditory feedback. This shift in LR for pressed voice under masking is consistent with results reported in the pitch- and amplitude-shifted feedback literature demonstrating that with pitch and amplitude perturbation participants change F_0 and intensity (Bauer et al., 2006;

Burnett et al., 1998; Burnett et al., 1997; Chen et al., 2007; Heinks-Maldonado & Houde, 2005; Leydon et al., 2003; Sivasankar et al., 2005; Xu et al., 2004). Our findings in the current study extend the previous perturbation work on F_0 and intensity to voice pattern suggesting that changes in voice pattern production under masking are dependent on the stability of the voice pattern.

The implications are twofold. First, the practical implication is that auditory feedback may be critical to emphasize in the training of new voice patterns during voice therapy. Some evidence was provided that breathy and normal voice might be considered relatively stable, as produced by participants in this study. In contrast, pressed voice might be considered less stable and, therefore, influenced by auditory feedback for these participants. Whereas pressed voice was less stable for the vocally healthy participants in our study, it might be more stable for individuals with certain conditions affecting voice. For those individuals, the "normal" voice pattern might introduce variability or less stability. In that case, for individuals with a voice disorder, heightened processing of auditory feedback might positively influence learning and, thus, rehabilitation outcomes as the individual moves from the more stable pressed voice to the less stable normal voice.

Second, from a theoretical perspective, the findings are consistent with suggestions elsewhere in the literature that auditory feedback is relevant to the control of voice for speech and singing (Bauer et al., 2006; Burnett et al., 1997; Elliott & Niemoeller, 1970; Gammon et al., 1971; Larson et al., 2007; Mürbe et al., 2002, 2004; Ternström et al., 1988; Ward & Burns, 1978). Specifically, the present findings suggest that auditory feedback may be relevant for voice qualities that are more variable (i.e., pressed voice in vocally trained women), but less relevant or even wholly irrelevant for voice qualities that are less variable (i.e., breathy and normal voice in vocally trained women). Evidence from the present study of a role of both voice pattern and auditory feedback in the control of LR suggests that further theorizing in voice motor control should seek to address both clinically relevant voice patterns and feedback processes.

Future Research Directions

Investigation should continue around the relevance of auditory feedback for theoretical and clinical issues surrounding voice. For theoretical issues, future investigations should continue to explore all sensory feedback factors that may influence control of voice; therefore, auditory and kinesthetic feedback are relevant. In addition, the influence of sensory feedback on voice control should consider not only normal voice productions but also "abnormal" voice productions as seen in patients with voice disorders. To heighten both practical and theoretical power, future investigations should also focus on changes in findings as a result of participants' skill level as well as tasks' ecological validity. In fact, the present study took into consideration such factors by studying tasks relevant to voice training and rehabilitation, carefully controlling for a prior skill level. Moreover, continuing to merge basic science investigations with clinical application will foster increased generalization across domains for an ultimate goal of improving the prevention, assessment, and treatment of voice disorders.

Turning to practical considerations, the question arises about the potential applicability of the results for clinical or other physical training practice. Possibly one area of interest would involve investigation into whether numeric standards can be established for LR for different voice patterns relevant to voice training and rehabilitation. If the numeric standards are feasible, then investigation should attempt to compare results across a numeric goal of LR versus a perceptual goal of LR. The relevance is that emerging notions suggest that voice training is best focused on helping individuals learn kinematic relations across subsystems in voice production, as opposed to fixed postures or behaviors within subsystems (e.g., Titze & Verdolini Abbott, 2010), and LR clearly captures one important facet of laryngeal–respiratory relations. Furthermore, such investigations should involve individuals with voice disorders to determine LR's ability to distinguish a dysphonic voice from a rehabilitated voice. Based on the findings from the current study, the implication is that physical training programs should emphasize feedback processes. In fact, the global voice therapy model emphasizes the recognition and production of "new voice" (i.e., improved vocal output achieved in therapy) and "old voice" (i.e., poor vocal output before therapy) by auditory and kinesthetic feedback at all levels of utterance length and cognitive complexity (Grillo, 2010). Advances in the understanding of how feedback and motor mechanisms interact in adaptive, biological systems are critical to the development of physical training and rehabilitation programs.

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