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Perceptual Evaluation of Vocal Fold Vibratory Asymmetry

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Objectives: Laryngeal vibratory asymmetry occurring with paresis may result in a perceptually normal or abnormal voice. The present study aims to determine the relationships between the degree of vibratory asymmetry, acoustic measures, and perception of sound stimuli.

Study Design: Animal Model of Voice Production, Perceptual Analysis of Voice.

Methods: In an in vivo canine model of phonation, symmetric and asymmetric laryngeal vibration were obtained via graded unilateral recurrent laryngeal nerve (RLN) stimulation simulating near paralysis to full activation. Phonation was performed at various contralateral RLN and bilateral superior laryngeal nerve stimulation levels. Naïve listeners rated the perceptual quality of 182 unique phonatory samples using a visual sort-and-rate task. Cepstral peak prominence (CPP) was calculated for each phonatory condition. The relationships among vibratory symmetry, CPP, and perceptual ratings were evaluated.

Results: A significant relationship emerged between RLN stimulation and perceptual rating, such that sound samples from low RLN levels were preferred to those from high RLN levels. When symmetric vibration was achieved at mid-RLN stimulation, listeners preferred samples from symmetric vibration over those from asymmetric vibration. However, when symmetry was achieved at high RLN levels, a strained voice quality resulted that listeners dispreferred over asymmetric conditions at lower RLN levels. CPP did not have a linear relationship with perceptual ratings.

Conclusions: Laryngeal vibratory asymmetry produces variable perceptual differences in phonatory sound quality. Though CPP has been correlated with dysphonia in previous research, its complex relationship with quality limits its usefulness as clinical marker of voice quality perception.

Key Words: Vibratory asymmetry, cepstral peak prominence, sort-and-rate, voice quality, in vivo phonation.

Level of Evidence: NA, basic science

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INTRODUCTION

Vibratory asymmetry is the most common finding in patients with laryngeal paresis,[1] and is observed during laryngeal videostroboscopy in dysphonic and normophonic speakers.[2] It results from asymmetric neuromuscular activation[3,4] and may reflect a range of denervation conditions, from subtle paresis to paralysis.[5] There is ongoing debate about its clinical significance, with some suggesting it is important to differentiate innocent vibratory asymmetries from clinically impactful ones.[6] One of the challenges to investigating the clinical impact of vibratory asymmetry is our inability to quantitatively measure the degree of paresis in patients. While some authors use laryngeal electromyography to evaluate laryngeal denervation, the technology remains qualitative.[6]

Our understanding of paresis is further complicated by conflicting results from studies relating asymmetry to voice quality. Samlan et al. found that improving phase and amplitude asymmetry improved perceived voice quality,[7] while Zhang et al. showed that left-right vibratory asymmetry did not produce perceptually significant changes in quality unless there was a change in vibratory mode.[8] Identifying reliable measures that predict and relate voice perception with voice production mechanisms would offer a step forward to consistently identifying voices as perceptually dysphonic or normal, and to distinguishing trivial from important asymmetries. Previous studies[9,10] have demonstrated that turbulent noise and the shape of the harmonic source spectrum[11] are strongly associated with pathologic voice quality. Time-based acoustic measures such as jitter, shimmer, and noise-to-harmonic ratio are unreliable predictors of dysphonia because they depend on periodicity of sound waves, which is often disrupted in dysphonia.[12] Cepstral peak prominence (CPP) has attracted more recent attention because it is robust against aperiodicity, and is thus a more reliable measure.[12]

Understanding the clinical utility of CPP requires assessing both its perceptual relevance and association with voice production. Previous work has shown that CPP predicts dysphonia arising from unilateral recurrent laryngeal nerve (RLN) paralysis[13] and correlates with

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perception of voice stimuli generated from kinematic speech production models of laryngeal asymmetry.[14] However, these relationships have not been tested simultaneously in an in vivo voice model.

The present study examines the relationships among vibratory asymmetry, CPP, and voice perception. Experiments were performed to determine the degree of vibratory asymmetry that results in a perceptually salient difference in voice quality, and the clinical utility of CPP for predicting these differences. Varying conditions of unilateral vocal fold paresis were simulated in an in vivo canine phonation model, and voice samples were recorded from each condition. Naïve listeners were then asked to rate the quality of these samples. Since CPP has predicted dysphonia in prior studies,[13,15] we predicted that listeners would rate voice samples with higher CPP (i.e., more harmonic energy and less spectral noise) more favorably. We also hypothesized that sound samples produced under conditions of greater phase asymmetry would include more inharmonic energy, and thus would be rated less preferentially.

MATERIALS AND METHODS

In Vivo Canine Phonation Model

An in vivo canine phonation model simulated conditions of unilateral vocal fold paresis. The Institutional Animal Research Committee approved the experimental protocol. Experiments were performed as previously described.[16] After induction of general anesthesia, a vertical midline incision exposed the larynx. Bilateral RLNs and external branches of the superior laryngeal nerves (SLNs) were identified. The internal branches of the SLNs and branches to the posterior cricoarytenoid muscle were divided to remove their effects during nerve stimulation. Tripolar cuff electrodes (Ardiem Medical, Indiana, PA) were placed around the RLNs and SLNs for neuromuscular stimulation. Nerves were stimulated with 0.1 msec cathodic pulses at 100 Hz for 1,500 msec. A low tracheotomy provided intraoperative ventilation and a subglottic tube provided warmed and humidified rostral airflow for phonation.

Neuromuscular Conditions Tested

Two experiments were performed on separate days, with one canine used per experiment. Varying degrees of unilateral vocal fold paresis were modeled by stimulation of the left RLN across 11 graded levels, ranging from threshold muscle activation (level 1, defined by a hint of muscle twitch, representing profound paresis, near paralysis, near 0% activation) to maximal muscle activation (level 11, defined by saturation of vocal fold adduction, representing vocal fold hyperadduction, or 100% activation). To perform graded stimulation, we first determined the stimulation current for threshold and maximal muscle activation. Stimulation current was then adjusted within that range to achieve the desired muscle activation level (50%, 80%, 90%, etc.). Accuracy of stimulation was also visually confirmed by reviewing high-speed video recordings for appropriate vocal fold movement, as described previously.[16]

Since speakers with vocal fold paresis activate other laryngeal muscles to compensate for weakened ones,[17] we modeled various combinations of neuromuscular compensation for each set of graded RLN stimulation. In one canine (experiment 1), the right RLN and SLN were stimulated at three constant levels (80%, 90%, and 100% of maximum activation), while the left SLN was stimulated at three constant levels (0%, 50%, and 100%). In the second canine (experiment 2), the right RLN was stimulated at three constant levels (80%, 90%, and 100% of maximum activation), while both the right and left SLNs were stimulated symmetrically at three constant levels (0%, 50%, and 100%). Trials were repeated at three airflow levels (500, 700, and 900 mL/sec). Higher airflow than normal human phonation was chosen to consistently elicit phonation during experiments modeling paresis/glottic insufficiency. Airflow levels used are consistent with reports of increased airflow requirements in human vocal fold paresis and paralysis.[18,19]

Fig. 1. The visual sort-and-rate task as implemented in Microsoft PowerPoint. Listeners clicked each icon to play the associated voice sample. They subsequently dragged each icon to sort the stimuli from best to worst in the box provided below. All icons in the slide belong to the same set of graded RLN stimulation. RLN = recurrent laryngeal nerve. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

Table I.
Summary of Main Experimental Results.

	Dependent Variables			
	Exp 1 Symmetry	Exp 1 Ratings	Exp 2 Symmetry	Exp 2 Ratings
Graded RLN level and neuromuscular compensation interaction	Significant effect Overall likelihood of symmetry peaked at mid-RLN levels	Significant effect Ratings with RLN stimulation levels 4 to 8 depended on compensation condition	Significant effect Overall likelihood of symmetry peaked at high RLN levels (10–11)	Significant effect Lower RLN levels had best ratings; exact rating depended on compensation condition
Symmetry		Significant effect Symmetric conditions = better ratings		Significant effect Moderately asymmetric conditions = better rating
CPP		Significant effect Weak correlation; poor ratings when CPP ≤ 10		Significant effect None or trivial correlation between CPP and rating

CPP = cepstral peak prominence; RLN = recurrent laryngeal nerve.

Measurement of Experimental Parameters

Audio samples from each phonatory condition were recorded using a probe microphone (Model 4128; Brüel and Kjær, Norcross, GA) mounted flush against the inner wall of the subglottic tube. Subglottic acoustic signals were used to control for vocal tract differences, minimize noise, and focus perception on

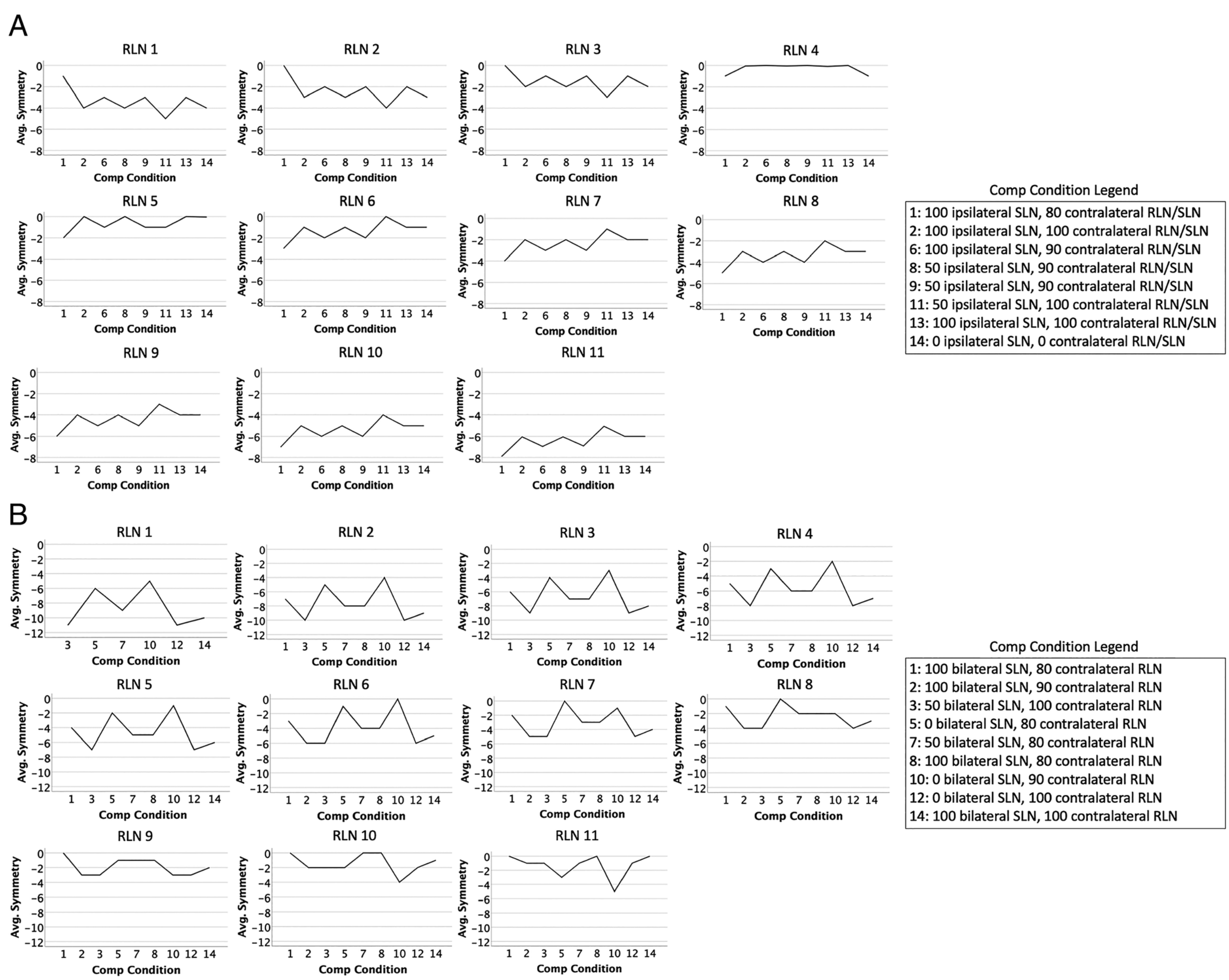

Fig. 2. Graded RLN level and neuromuscular compensation (bilateral SLN, contralateral RLN) interacted to determine symmetric or asymmetric vibration in both experiments. (A) In experiment 1, increasing RLN stimulation increased and then decreased the likelihood of symmetric vibration, depending on compensation condition. (B) In experiment 2, the likelihood of symmetric vibration increased with increasing RLN stimulation level, and the pattern of increase was determined by compensation condition. RLN = recurrent laryngeal nerve; SLN = superior laryngeal nerve.

the voice source. A high-speed video camera (Phantom v210, Vision Research Inc., Wayne, NJ) recorded laryngeal posture change at each stimulation level at 3,000 frames/sec. Vibratory symmetry/asymmetry was determined from these recordings by identifying the opening phase in frame-by-frame analysis. Conditions were deemed symmetric when both glottal edges opened simultaneously, and asymmetric when the glottis opened first on one side. The symmetric condition was labeled "0" and remaining phonatory conditions within the set were labeled to reflect levels away from vibratory symmetry. For example, if RLN stimulation level 5 was symmetric, then both levels 4 and 6 would be labeled "−1." Larger negative values thus reflected greater degrees of phase asymmetry.

Acoustic Measures and Perceptual Testing

CPP for each sound sample was calculated from a 700 msec segment of stable phonation, using previously described parameters[20] with Praat software (Version 6.1.09, Boersma). Because differences in loudness may overshadow other differences in voice quality,[21] the average intensity of each sound sample was normalized to 70 dB using Praat prior to perceptual testing.

Forty-two (one listener contributed partial results and was lost to follow up) naïve listeners (19 male) with self-reported normal hearing and little to no prior experience with auditory-perceptual analysis participated in this experiment. This study was approved by the Institutional Review Board at the University of California, Los Angeles. Perceptual studies were conducted using a visual sort-and-rate task implemented in Microsoft PowerPoint.[22] These experiments were performed virtually because of restrictions on in-person gatherings due to COVID-19. After providing informed consent, participants were emailed PowerPoint presentations from a single animal experiment to determine test-retest reliability. Each presentation included 7 to 8 slides in random order, and each slide contained sound samples from the same trial (each set of graded stimulation). Each sound sample was linked to a unique icon. Icons were arranged randomly above an empty box labeled "best" on the right side and "worst" on the left side (Fig. 1).

Listeners were instructed to listen to each sound sample and rate it from "best" to "worst" by dragging the corresponding

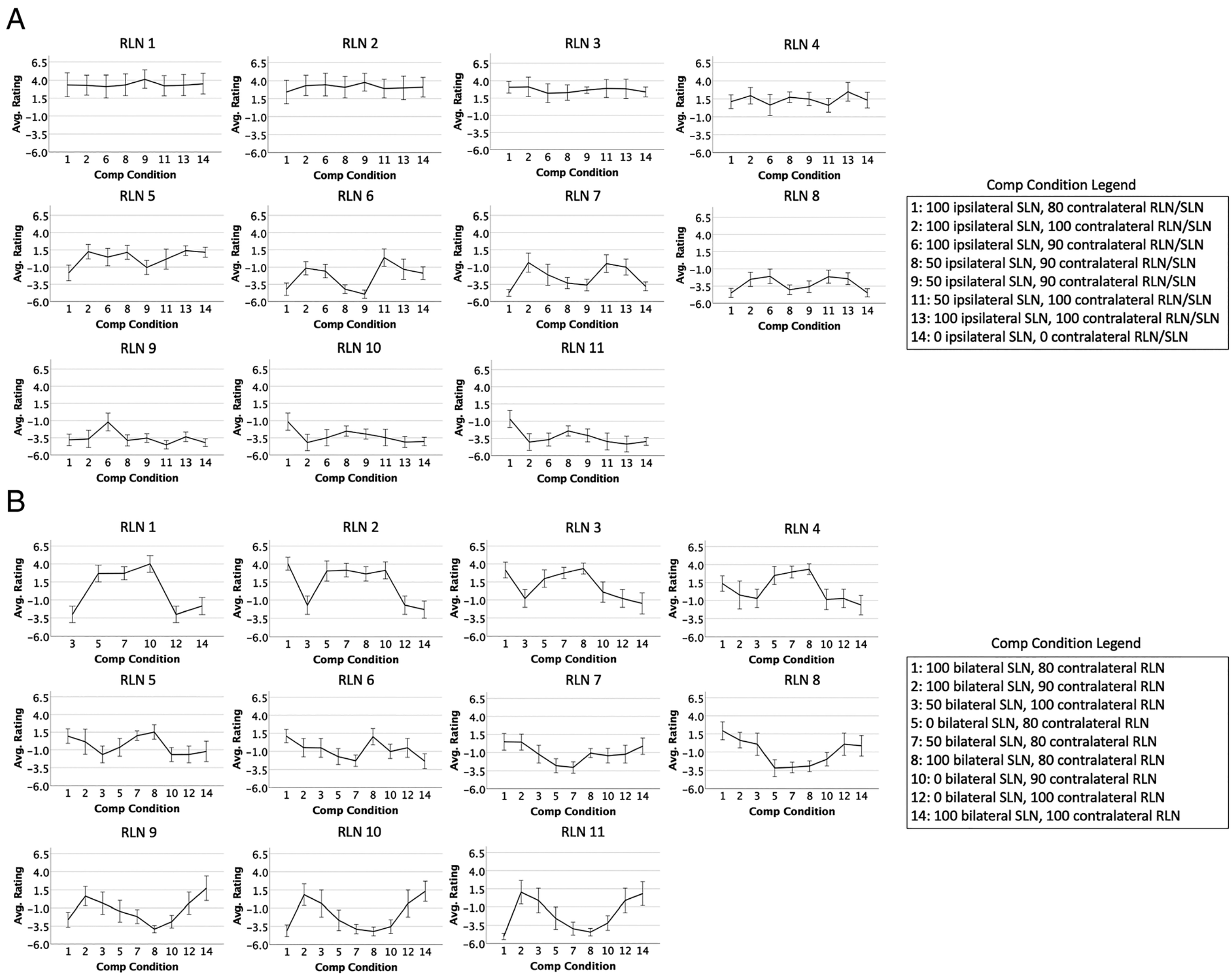

Fig. 3. Interaction between RLN level and neuromuscular compensation on perceptual rating in both experiments. Error bars represent 95% confidence intervals. (A) In experiment 1, sound samples from low RLN levels overall had high ratings, sound samples from high RLN levels overall had low ratings, and sound samples from levels 4 to 8 had varying ratings depending on contralateral compensation. (B) In experiment 2, this relationship was also observed, although compensation condition had more of an effect when comparing ratings from the same RLN level. RLN = recurrent laryngeal nerve.

icon to the appropriate location in the box. If two or more sound samples were perceived to be equally acceptable, participants stacked the icons on top of each other. Listeners were instructed to perform the experiment with headphones, in a quiet area without interruptions, and to play stimuli at a comfortable volume for judging sound quality. They were welcome to play the stimuli within a trial as often as they liked, in any order, but were instructed not to advance to the next slide until they were finished sorting all icons in the current slide. There were no time limits. Some stimuli were rated twice to determine intrarater reliability.

Each sound sample's perceptual score was determined by the absolute position of its icon in the rating box. Location in the box was manually extracted by displaying a vertical guide in PowerPoint and measuring each icon's position on the embedded ruler. A "0" value indicated that the icon was placed in the middle of the box, while positive and negative values indicated that the sound was rated toward the "best" or "worst" side, respectively.

Data Analysis

SYSTAT (Version 13.1; San Jose, CA) and SPSS (Version 27; Chicago, IL) were used for statistical analysis. Data from all trials per experiment were aggregated. Data from different experimental days were analyzed separately. The relationship between RLN stimulation, compensation condition, and symmetry was analyzed using two-way analysis of variance (ANOVA). Two-way ANOVA also compared perceptual ratings across different RLN levels and compensation models. One-way ANOVA was used to relate symmetry level and perception. Significant ANOVA results were analyzed using post hoc Tukey's tests. Spearman's correlation related CPP and perceptual rating. Significance was defined as $P < .05$.

RESULTS

A total of 182 unique sound samples were perceptually rated by listeners. Average CPP for experiments 1 and 2 were 13.3 ± 3.75 and 7.99 ± 3.06, respectively. Listeners were consistent in their ratings between trials, indicating adequate test-retest reliability (Pearson's $r = 0.52$, $P < .05$). Table I summarizes our main experimental findings.

Experiment 1: Contralateral Combined SLN/RLN and Ipsilateral SLN Compensation Model

A two-way ANOVA examining the effects of graded RLN stimulation level and neuromuscular compensation (contralateral RLN, bilateral SLNs) on vibratory symmetry showed a significant relationship between vocal fold symmetry and both RLN level [$F(10,1716) = 58{,}485.370$, $P < .05$], and neuromuscular compensation [$F(7,1716) = 1{,}930.854$, $P < .05$]. There was a significant interaction between RLN level and neuromuscular compensation on symmetry [$F(70,1716) = 1{,}620.117$, $P < .05$]. The overall likelihood of symmetry first increased, then decreased, with increasing RLN stimulation, with the precise pattern dependent on compensation condition (Fig. 2A).

The effects of graded RLN level and compensation condition on perceptual ratings were analyzed with a second two-way ANOVA. There was a significant relationship between RLN level [$F(10,1716) = 232.572$, $P < .05$] and compensation condition [$F(7,1716) = 4.208$, $P < .05$] on perceptual ratings, along with a significant interaction [Fig. 3A; $F(70,1716) = 4.249$, $P < .05$]. Across all compensation conditions, sound samples arising from RLN levels 1 to 3 were rated better by listeners, voice samples from RLN conditions 9 to 11 were less preferred, while ratings of sound samples from RLN conditions 4 to 8 varied with compensation condition.

Figure 4A shows the relationship between symmetry and perceptual rating. One-way ANOVA showed a significant effect of vibratory asymmetry on perceptual ratings [adjusted $R^2 = 0.16$; $F(8,1795) = 42.198$, $P < .05$]. Post hoc Tukey's tests revealed that mean perceptual ratings were significantly higher in symmetric conditions versus all but the most asymmetric condition (−8). Finally, there was a weak correlation between CPP values and ratings ($r_s = 0.205$, $P < .05$; Fig. 5A). However, a CPP value of 10 represented a threshold below which stimuli were always perceived negatively, while positive ratings were always associated with CPP values above 10.

Experiment 2: Combined Bilateral SLN and Contralateral RLN Compensation Model

A two-way ANOVA examining the effects of graded RLN stimulation and neuromuscular compensation on

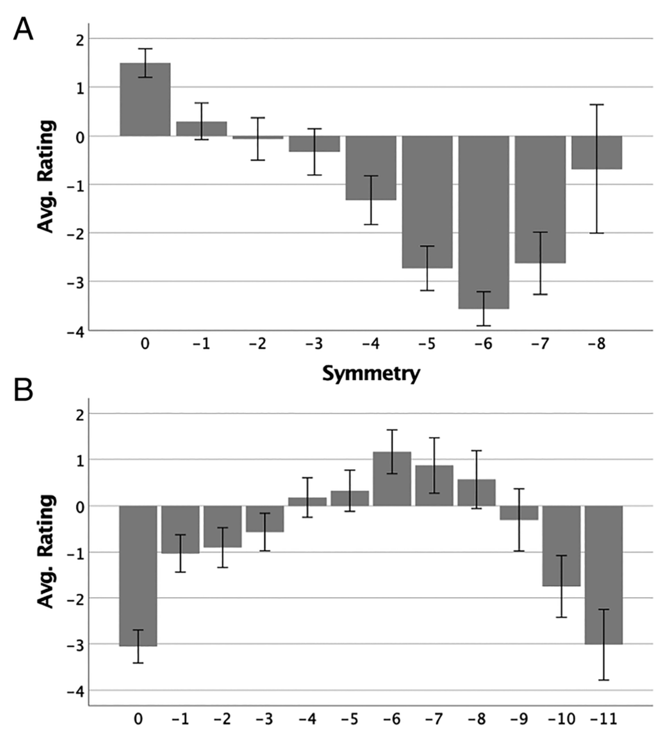

Fig. 4. Effects of vibratory symmetry/asymmetry on mean perceptual rating. Zero represents vocal fold symmetry and negative values represent incremental levels of asymmetry. Error bars represent 95% confidence intervals. (A) In experiment 1, symmetric conditions were associated with higher ratings overall. (B) In experiment 2, moderately asymmetric conditions (−4, −5, −6, −7, −8) were associated with superior ratings.

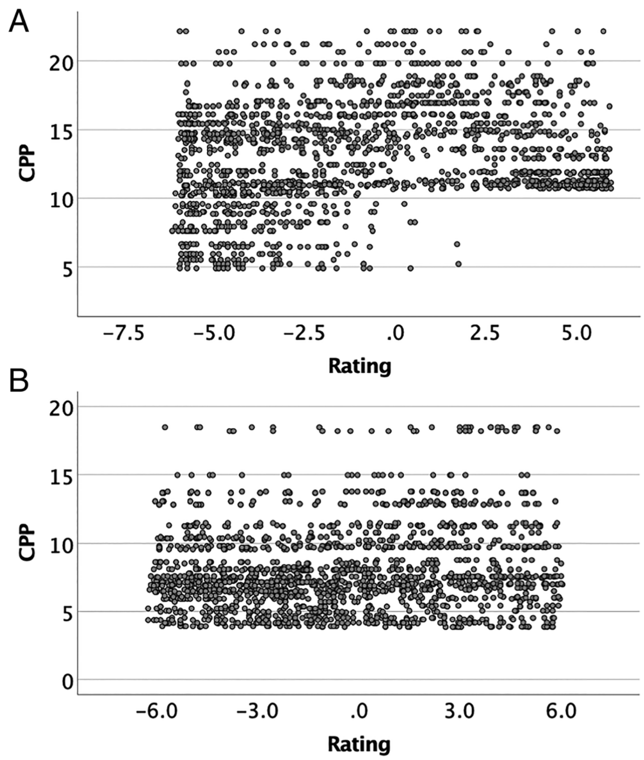

Fig. 5. Relationship between CPP and perceptual rating in experiments 1 and 2. (A) In experiment 1, there was a weak correlation between CPP and perceptual rating; a CPP value of ≤10 represented a threshold for poor ratings. (B) In experiment 2, there was a negligible correlation between CPP and perceptual rating. CPP = cepstral peak prominence.

symmetry showed a significant relationship between symmetry and both RLN level [$F(10,1840) = 8.73 \times 10^{31}$, $P < .05$], and neuromuscular compensation [$F(8,1840) = 3.34 \times 10^{31}$, $P < .05$]. There was also a significant interaction between RLN level and neuromuscular compensation on symmetry [$F(73,1840) = 3.44 \times 10^{30}$, $P < .05$]. As RLN level increased, the likelihood of symmetric vibration also increased, although the precise pattern of increase varied somewhat by compensation condition (Fig. 2B).

A second two-way ANOVA determined the relationship between graded RLN level, compensation condition, and perceptual rating. There were significant differences in perceptual ratings across RLN stimulation levels [$F(10,1880) = 35.587$, $P < .05$] and across compensation models [$F(8,1880) = 10.02$, $P < .05$], along with a significant interaction between compensation model and RLN level [$F(75,1880) = 12.46$, $P < .05$; Fig. 3B]. On average, phonation samples from low RLN levels were rated better and samples from high RLN levels were rated worse, as observed in experiment 1. However, ratings varied more across RLN levels depending on neuromuscular compensation condition, reflecting the greater interaction between RLN level and contralateral stimulation.

The relationship between symmetry level and perceptual rating is shown in Figure 4B. There was a significant relationship between symmetry level and perceptual rating [adjusted $R^2 = 0.129$; $F(11,1920) = 26.908$, $P < .05$]. Post hoc analysis revealed that moderately asymmetric conditions (−4 through −8) received higher mean perceptual ratings than symmetric (0), mildly asymmetric (−1, −2, −3), or severely asymmetric conditions (−9, −10, −11). Post hoc listening suggested a bifurcation in quality with increasing asymmetry: The most symmetric cases were characterized by harsh, strained, creaky phonation, while the least symmetric conditions were weak and breathy. Listeners dispreferred both these extremes. Last, there was a significant but negligible correlation between CPP and perceptual rating ($r_s = 0.102$, $P < .05$, Fig. 5B).

DISCUSSION

Since vibratory asymmetry occurs in both dysphonic and normophonic speakers,[1,2] it can be difficult to distinguish clinically significant asymmetries from benign ones. Quantitative measurement of vocal fold paresis severity has not been implemented in clinical practice; therefore, it is impossible to determine how much asymmetry is needed to cause a perceptually salient difference in voice. In the present study, we were able to simulate vibratory asymmetry in an in vivo phonation model to investigate this relationship. We hypothesized that the relationships among neuromuscular stimulation, vibratory symmetry, CPP, and voice quality in paretic states could be understood through a chain of associations, by which decreasing symmetry leads to increased spectral noise/decreased CPP, which in turn leads to less acceptable voice quality.

Graded RLN stimulation and neuromuscular compensation (with bilateral SLN, contralateral RLN stimulation) did indeed contribute to vibratory symmetry in both experiments, as hypothesized. While we originally predicted that symmetric conditions would receive better perceptual ratings, our results were more nuanced. In experiment 1, symmetric conditions were rated significantly better than even slightly asymmetric conditions. While prior work[21,23] has proposed that minor vibratory asymmetries may reflect natural complexities of vibration that do not disrupt phonation, in this case, these differences were salient to naïve listeners. However, in experiment 2, listeners favored sounds from moderately asymmetric conditions. We speculate that these differences arose from the differing RLN conditions that determined symmetry. Vibration was symmetric at RLN levels 4 to 5 in experiment 1 and at levels 10 to 11 in experiment 2, presumably due to the differences in compensatory muscle activation. Across all conditions, low levels of RLN stimulation produced sounds that were weak and breathy, but stimuli became harsher and more strained with high levels of RLN stimulation. In experiment 2, when symmetry occurred at high RLN levels, the strained quality of the voices offset the reduction in spectral noise from symmetric vibration, resulting in perceptually abnormal voices. In both experiments, listeners generally preferred sound samples arising from low RLN stimulation. This again emphasizes that listeners preferred weaker and breathier voices, even if vibration was asymmetric, over strained voices.

While CPP has been shown to predict perceptual voice quality in studies using kinematic voice production models,[14] we found a weak to negligible relationship between CPP and perceptual rating. A CPP value of 10 or less represented a threshold for poor voice quality in experiment 1. This relationship was not seen in experiment 2, likely because these sound samples had lower CPP values on average. CPP is a computationally robust acoustic measure that reflects the ratio between harmonic energy and turbulent noise.[24] While levels of harmonic and inharmonic energy are important determinants of voice quality, they do not fully explain the complexities of human perception. Other properties such as pitch, loudness, and shape of the harmonic source spectrum also influence voice perception,[21] without necessarily changing CPP. While we controlled for loudness in this study, we did not control for pitch. In fact, increasing RLN stimulation also increases the amount of high frequency harmonic excitation.[25] While this increases harmonic energy and CPP, it also offers a variable that influences perception that CPP does not account for.[26]

Although this study contributes to our understanding of voice perception in vocal paresis, several limitations are apparent. Sound samples came from an in vivo canine larynx, which closely resembles the human larynx in anatomy and physiology.[16] Although there are inherent differences between human and canine sounds, these studies are impossible to perform with in vivo human voices because we cannot quantitatively measure or control the degree of laryngeal denervation. Some of our results may be attributed to inherent differences in vocal fold physiology between the animals; however, ethical considerations preclude the use of additional canines per experiment, and we rely on the minimum number needed to obtain meaningful data. These findings are still valuable for understanding the relationship between laryngeal asymmetry, CPP, and perception. Because perceptual studies were performed remotely, listeners likely varied in listening devices used and volume at which they played sound stimuli. Although this could influence perceptual results, it also contributes to the external validity of our findings since differences in listening environment are inherent to daily hearing practices. Listeners were also limited to our sample of 11 stimuli per slide, thus introducing a potential source of contextual bias. Future studies could expand upon our results by including a wider range of stimuli per trial to more comprehensively capture and compare the different determinants of voice perception.

CONCLUSION

This study determined the relationship between vocal fold paresis, CPP, and perception of voice quality. We observed a complicated relationship between vibratory symmetry and perception. When symmetric vibration occurred at mid-RLN stimulation levels, listeners preferred these voices over those from asymmetric vibration. However, when symmetric vibration occurred at high RLN levels, listeners preferred asymmetric conditions over the strained voices resulting from high RLN stimulation. Overall, softer voices were rated favorably. We did not observe a linear relationship between CPP and perception, presumably because CPP did not account for other acoustic features such as pitch that were salient to our listeners.

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