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Modulation of Neck Intermuscular Beta Coherence During Voice and Speech Production

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Purpose: The purpose of this study was to better understand neck intermuscular beta coherence (15–35 Hz; NIBcoh) in healthy individuals, with respect to modulation by behavioral tasks.
Method: Mean NIBcoh was measured using surface electromyography at 2 anterior neck locations in 10 individuals during normal speech, static nonspeech maneuvers, "clear" speech (intentionally produced to maximize intelligibility), divided-attention speech, singing, and mimicked hyperfunctional speech.
Results: An analysis of variance showed significant effects of both individual and condition (p = .001) on the mean beta-band intermuscular coherence. Dunnett's simultaneous paired t tests found decreased NIBcoh during low-attention speech, singing, and hyperfunctional speech (p_{adj} < .05), but no significant difference in NIBcoh during nonspeech tasks or clear speech production relative to normal speech.
Conclusions: Compared with normal speech, mean NIBcoh was decreased in a divided-attention speech task, but clear speech did not result in increased mean coherence relative to normal speech, possibly due to ceiling effects caused by heightened attention and precision during experimental recording. Mimicking a strained, hyperfunctional voice resulted in a reduction in mean beta intermuscular coherence quantitatively and qualitatively similar to the lowered values of mean beta coherence seen in individuals with vocal nodules relative to individuals with normal voice.

Key Words: voice, speech disorders, electromyography

It has recently been discovered that the anterior neck intermuscular beta coherence (NIBcoh) is significantly decreased in individuals with vocal nodules when compared with healthy normal speakers (Stepp, Hillman, & Heaton, 2010). Stepp et al. hypothesized that NIBcoh could possibly be used as an objective measure of vocal hyperfunction, which has been defined by Hillman, Holmberg, Perkell, Walsh, and Vaughan (1989) as "conditions of abuse and/or misuse of the vocal mechanism due to excessive and/or 'imbalanced' muscular forces" (p. 373), characterized by excessive laryngeal and paralaryngeal tension (Aronson, 1980; Dworkin, Meleca, & Abkarian, 2000; Koufman & Blalock, 1991; Morrison, Rammage, Belisle, Pullan, & Nichol, 1983; Roy, Ford, & Bless, 1996). Although these results show promise for the use of coherence-based measures for studying disordered voice production, they also prompt a variety of further questions about the nature of this measure and how it may be modulated. One goal of the present study was to better understand NIBcoh in the context of speech and voice production.

An object of much recent neuroscience research has been the area of physiological coherence (i.e., measurement of coherence on physiologic signals). Coherence is a frequency domain measure of the linear dependency or strength of coupling between two processes (e.g., Halliday et al., 1995). The coherence function, $|R_{xy}(\lambda)|^2$, can be defined as in Equation 1 below, where f_{xx} represents the auto-spectra of a time series $x(t)$, f_{yy} the auto-spectra of $y(t)$, and f_{xy} the cross-spectra of the two. In this study, intermuscular coherence was calculated using this equation on two electromyographic (EMG) signals.

$$|R_{xy}(\lambda)|^2 = \frac{|f_{xy}(\lambda)|^2}{f_{xx}(\lambda)f_{yy}(\lambda)}. \quad (1)$$

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Coherence has been used extensively to assess the oscillatory coupling between the central nervous system and EMG by computing coherence between EMG and magnetoencephalographic (MEG) signals or electroencephalographic (EEG) signals (e.g., Mima, Matsuoka, & Hallett, 2001; Riddle & Baker, 2005). Furthermore, coherence between multiple EMG signals (intermuscular coherence) can be used to measure the common presynaptic drive to motor neurons (P. Brown, Farmer, Halliday, Marsden, & Rosenberg, 1999).

Muscle is thought to be driven by a number of different physiological oscillations at varying frequencies (see Grosse, Cassidy, & Brown, 2002, for a review). The frequencies at which physiological oscillations occur appear to be characteristic of the function of distinct neural circuits and have been categorized into distinct bands such as alpha (8–13 Hz), beta (15–35 Hz), gamma (30–70 Hz), and others. It is generally thought that the beta and low gamma bands originate primarily from the primary motor cortex (Grosse et al., 2002). The beta band is typically associated with production of static motor tasks and is reduced with movement onset (e.g., Kilner et al., 1999). Furthermore, coherence in the beta band has been shown to decrease with divided attention and to increase with increased precision of motor tasks (Kristeva-Feige, Fritsch, Timmer, & Lücking, 2002). Intermuscular coherence measurements reflect all oscillatory presynaptic drives to lower motoneurons. However, the intermuscular coherence in the beta band has been shown to be qualitatively similar to corticomuscular coherence, both in healthy individuals as well as in individuals with cortical myoclonus (P. Brown et al., 1999; Kilner et al., 1999), leading to the hypothesis that beta-band intermuscular coherence is due to cortical oscillatory drive.

Physiological coherence has not yet been widely adopted in speech research. Smith and Denny (1990) collected surface EMG (sEMG) from the right and left ventrolateral chest wall and right and left masseter of eight healthy normal individuals while they performed deep breathing, speech production, speechlike breathing, chewing, and rhythmic clenching tasks. They found that speech and speech breathing caused a reduction in 60- to 100-Hz intermuscular coherence measured bilaterally from the chest wall, relative to deep breathing. Furthermore, although chewing elicited high 20- to 60-Hz coherence measured bilaterally from the masseters, these levels were reduced during speech.

Disordered populations that have been studied during speech using coherence include persons who stutter (Denny & Smith, 1992, 2000), individuals with Parkinson's disease (Caviness, Liss, Adler, & Evidente, 2006), and individuals with vocal nodules (Stepp et al., 2010). Denny and Smith (1992) examined 17 persons who stutter using hooked wire EMG and sEMG from muscles of the lip, jaw, and anterior neck during speech. Intermuscular coherence between the two strongest signals was compared between their stuttered and fluent speech. Although some participants showed differences in coherence between stuttered and fluent speech, this was not an overall finding in all participants. Denny and Smith (2000) further examined intermuscular coherence measured bilaterally from the chest wall in 10 healthy normal speakers relative to 10 persons who stutter. All healthy controls and most persons who stutter showed coherence in the 60–110 Hz range during speech that was less than or equal to that found during deep breathing, although some of the persons who stutter showed the opposite pattern: higher coherence during speech than in the deep breathing condition. Using EEG and sEMG of the orbicularis oris muscles, Caviness et al. (2006) examined corticomuscular coherence in 20 healthy participants and 20 individuals with Parkinson's disease (ON medication) during both speech and nonspeech tasks. Corticomuscular coherence between the supplementary motor area and the periphery was decreased in the 8–30 Hz range for individuals with Parkinson's disease relative to healthy controls during sustained pucker, pucker-smile, speechlike behaviors, and both single- and multiple-word tasks. However, differences between groups were less extreme during speech than nonspeech tasks.

The more recent work of Stepp et al. (2010) measured anterior NIBcoh in 18 individuals with vocal nodules and 18 individuals with healthy normal voice during reading and spontaneous speech tasks using sEMG. No difference in NIBcoh was seen as a function of speech type; however, individuals with vocal nodules showed significantly decreased NIBcoh when compared with healthy normal speakers. This finding not only indicates promise for future use of coherence-based measures in speech and voice science but also prompts further study into this measure and how it may be modulated. Assuming that NIBcoh is indicative of cortical-level oscillatory drive to neck strap muscle, behavioral changes known to affect corticomuscular beta-band coherence in nonspeech systems and tasks may also modulate NIBcoh during speech. The purpose of this research was to further investigate the use of NIBcoh in speech research by determining the effects of increased and decreased attention and precision, singing, production of strained (hyperfunctional) voice, and static (constant force) nonspeech maneuvers. Muscle contraction without movement (static nonspeech maneuvers) were hypothesized to increase NIBcoh, given the previous findings in the upper limb (Kilner et al., 1999). Decreases in attention and precision during speech were hypothesized to decrease NIBcoh, given the reduction in beta corticomuscular coherence with decreased attention and precision in an upper limb task (Kristeva-Feige et al., 2002). Singing tasks were included in the study for exploratory reasons, because the neural control of singing and speech has shown overall differences in the relevant neural networks (S. Brown et al., 2009); thus, the alternative hypothesis for NIBcoh during singing tasks was that there would be a difference relative to that found during normal speech, but no specific hypotheses about the nature of this difference were made a priori. In addition, the effect of singing background on NIBcoh during singing and typical speech was examined to ensure that differences seen in NIBcoh during singing were not a result of poor neural control over singing (poor singing ability). Production of hyperfunctional voice was hypothesized to lead to decreased NIBcoh, given the findings of Stepp et al. (2010).

Method

Participants and Recording Procedures

Participants were 10 female volunteers with healthy normal voice (mean age = 25.0 years, *SD* = 2.6 years). They reported no complaints related to their voice, and no abnormal pathology of the larynx was observed during standard digital videoendoscopy with stroboscopy performed by a certified speech-language pathologist (SLP). Informed consent was obtained from all participants in compliance with the Institutional Review Board of the Massachusetts General Hospital. Previous singing experience of each of the participants was catalogued and is shown in Table 1.

Simultaneous neck sEMG and acoustic signals from a lavalier microphone (Sennheiser MKE2-P-K, Wedemark, Germany) were filtered and digitally recorded at 20 kHz with Delsys hardware (Bagnoli Desktop System, Boston, MA) and software (EMGworks 3.3). The neck of each participant was prepared for electrode placement by cleaning the neck surface with an alcohol pad and "peeling" (exfoliation) with tape to reduce electrode-skin impedance, noise, DC voltages, and motion artifacts. Neck sEMG was recorded with two Delsys 3.1 double differential surface electrodes placed on the neck surface, parallel to underlying muscle fibers. Each electrode consisted of three 10-mm silver bars with interbar distances of 10 mm. Double differential electrodes were chosen instead of single differential electrodes in order to increase spatial selectivity and to minimize electrical cross-talk between the two electrodes.

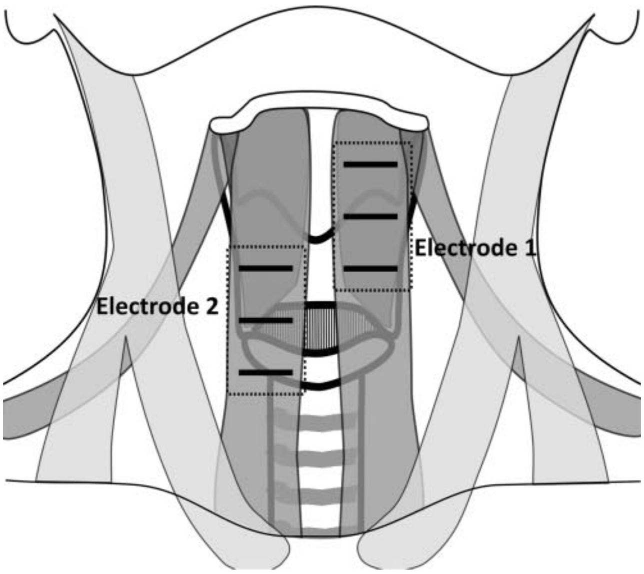
The two electrodes were placed on the right and left anterior neck surface. Electrode 1 was centered approximately 1 cm lateral to the neck midline, as far superior as was possible without impeding the jaw opening, superficial to fibers of the thyrohyoid and sternohyoid muscles, and to some degree the omohyoid. Electrode 2 was placed contralateral to Electrode 1. It was centered vertically on the gap between the cricoid and thyroid cartilages of the larynx, and centered 1 cm lateral to the midline contralateral to Electrode 1, superficial to the cricothyroid, sternothyroid, and sternohyoid muscles. However, based on our previous examinations of sEMG recordings during pitch glides (Stepp et al., 2010), it is doubtful that cricothyroid contraction contributed much energy to the sEMG due to its relatively deep position. The platysma muscle likely contributed to some degree to the activity recorded at both electrode locations. A schematic indicating electrode locations is shown in Figure 1. A ground electrode was placed on the superior aspect of the participant's left shoulder. The sEMG recordings were preamplified and filtered using the Delsys Bagnoli system set to a gain of 1,000, with a bandpass filter with roll-off frequencies of 20 Hz and 450 Hz. All recordings were monitored by the experimenters in real time to ensure signal integrity, and no recordings included movement artifact.

Table 1. Singing background of participants.

Participant	Singing experience	Normal speech NIBcoh	Singing NIBcoh	Classified as singer?
P1	None—required grade school music class.	0.20	0.11	N
P2	None—required grade school music class.	0.17	0.06	N
P3	2 years of voice lessons, college music courses and choirs.	0.38	0.21	Y
P4	Choir and voice lessons in high school.	0.26	0.13	Y
P5	None—required grade school and middle school choirs.	0.04	0.10	N
P6	High school musical theater.	0.14	0.01	Y
P7	None—required grade school music class.	0.11	0.04	N
P8	None—required grade school music class.	0.17	0.19	N
P9	None—required grade school and middle school choirs.	0.38	0.25	N
P10	No formal training; frequent solo and group singer of rock, a capella, and musical theater in high school, college, and graduate school.	0.27	0.18	Y

Note. NIBcoh = neck intermuscular beta coherence.

Figure 1. A schematic of the anterior neck is shown, with the locations of the two double-differential surface electromyographic (sEMG) electrode locations.



Tasks

The recording procedure consisted of a variety of specific tasks designed to provide samples of the following conditions: static nonspeech maneuvers, normal natural speech, clear speech (increased attention and precision during speech production), speech production under divided attention, singing, and speech while mimicking hyperfunctional voice. Tasks were ordered as listed, with all participants beginning with static nonspeech maneuvers and ending with hyperfunctional voice tasks. Table 2 summarizes the conditions that were tested as well as the specific tasks used to evoke those conditions. At the end of each recording session, maximal voluntary contraction maneuvers were performed for the purpose of normalizing root-mean-square (RMS) sEMG data (see the Data Analysis section) by maximal neck contraction against manual resistance.

Table 2. Conditions and tasks for the recording procedure.

Condition	Specific task
Static nonspeech	Tongue retraction Static-resisted force
Normal speech	Normal speech: Spontaneous Normal speech: The "Rainbow Passage"
Clear speech	Clear speech: Spontaneous Clear speech: The "Rainbow Passage"
Divided attention speech	Backward counting by 7 s
Singing	"Happy Birthday" "Rudolph the Red-Nosed Reindeer"
Hyperfunctional speech	Hyperfunctional speech: Spontaneous Hyperfunctional speech: The "Rainbow Passage"

Static nonspeech tasks consisted of tongue retraction and a constant resisted force. To complete the tongue retraction task, each participant was asked to attempt to place the tip of her tongue on her back right molar and to hold it there, an activity known to elicit strong strap muscle activation without movement (e.g., Ohala & Hirose, 1970). Tongue retraction was performed while the participant watched visual feedback of her real-time sEMG signals. She was asked to keep this activity steady for approximately 45 s. For the constant resisted force, a dynamometer (Chatillon DPP-50, Ametek, Inc., Paoli, PA) with analog output that was outfitted with a chin rest was placed under the chin of each participant. Each participant was asked to supply constant downward force on the device such that the reading was always at 5 lb_f for approximately 1 min. No participant had any problems completing either static nonspeech task correctly.

Normal, clear, and hyperfunctional speech production tasks consisted of reading "The Rainbow Passage" (Fairbanks, 1960) and producing spontaneous speech. Spontaneous speech for each condition was produced in response to a variety of available prompts, which were selected by the participants (e.g., "What did you do last weekend?"). The Rainbow Passage was typically produced for 30–45 s. Spontaneous speech samples were approximately 1 min in length. For the normal speech condition, individuals were instructed to read or talk "as normally and naturally as possible." Clear speech (e.g., Perkell, Zandipour, Matthies, & Lane, 2002) was used as a way of encouraging increased attention and precision during speech tasks. During the clear speech production, participants were asked to speak as if they were talking with someone who had a difficult time understanding them, whether due to hearing loss or a first language other than English. Individuals were coached into speaking with a mimicked hyperfunctional voice by the request to speak as if they had "a hard time producing their voice" and modeling of hyperfunctional production by the first author. This coaching took less than 2 min of listening and practice by the participant. No participant had any problems completing any of these speech tasks correctly. In order to collect speech under divided attention, participants were given 60 s to count backwards as quickly as possible in increments of 7. These recordings were typically approximately 45 s in length. Participants uniformly reported this task as difficult, but all were able to produce continous speech during the recording.

The singing condition consisted of two tasks: singing "Happy Birthday" and "Rudolph the Red-Nosed Reindeer." These two songs were chosen to ensure that all participants would be familiar with the songs used. Text of the lyrics of the two songs was provided. All participants were adequately familiar with the two songs and were able to sing them without problems in approximately 1.5 min for the two songs combined.

Data Analysis

Audio signals were examined offline using visual inspection and listening to the audio signal to determine periods of task production. For speech or singing tasks, analysis times were chosen manually from approximately 0.5 s before and after continuous speech or singing production.

The sEMG signals were full-wave rectified, and any DC offset was removed from each sample. Coherence and phase estimates were calculated over a sliding 16,384-point (~820-ms) Hamming window with a 16,384-point fast Fourier transform, using 50% overlap, mimicking the methods used in Halliday et al. (1995), using custom software written in MATLAB. For each sample, a 5% significance level for coherence was determined on the basis of sample length (e.g., Halliday et al., 1995); the highest value found here was <.04. Average values of NIBcoh were calculated by averaging the coherence over the full 15–35 Hz frequency range. No consistent differences were noted between dual tasks testing the same condition (e.g., spontaneous vs. read speech, "Happy Birthday" vs. "Rudolph the Red-Nosed Reindeer"), so tasks for each condition were averaged to provide a single measure of NIBcoh for each participant and condition.

The mean of the RMS values of sEMG collected from both electrodes during samples was computed in 1-s windows (no overlap) using custom MATLAB software. Mean RMS values were normalized as the percentage of maximal voluntary contraction. For the two electrodes, the average of the mean-normalized RMS during the tasks was calculated to provide a single measure of the mean magnitude of the sEMG collected. The absolute difference between the mean-normalized RMS of the two electrodes was also calculated to provide a measure of the difference in signal magnitude between the two electrode locations. As with the NIBcoh, RMS-based measures for multiple tasks in a condition were averaged.

Samples of clear and hyperfunctional speech were further examined in order to ensure true differences in speech production relative to the normal speech condition. Samples of the reading passage during normal speech and speech with mimicked hyperfunctional voice were perceptually rated by a certified SLP for the presence of "strain" using the CAPE-V (Kempster, Gerratt, Verdolini Abbott, Barkmeier-Kraemer, & Hillman, 2009). Approximately 30% of samples were rerated by the SLP and by a second certified SLP, yielding interrater reliability as measured by Pearson's r of .75 and intrarater reliability of .99. The samples of the reading passage during normal and clear speech production were analyzed for mean syllable rate (total number of syllables produced/total speech time).

Statistical Analysis

Statistical testing was performed by analysis of variance (ANOVA), post hoc Dunnett's simultaneous paired t tests, and Student's t tests using Minitab statistical software. A two-factor ANOVA on the NIBcoh was used to examine possible effects of individual and condition. Dunnett's simultaneous paired t tests were used to test differences in NIBcoh between normal speech and the other conditions. Paired one-sided tests were used to test the hypotheses that NIBcoh during normal speech was higher than that during divided-attention and hyperfunctional speech, and lower than that during static nonspeech and clear speech. A paired two-sided test was performed to test the hypothesis that NIBcoh during normal speech was not equal to that during singing.

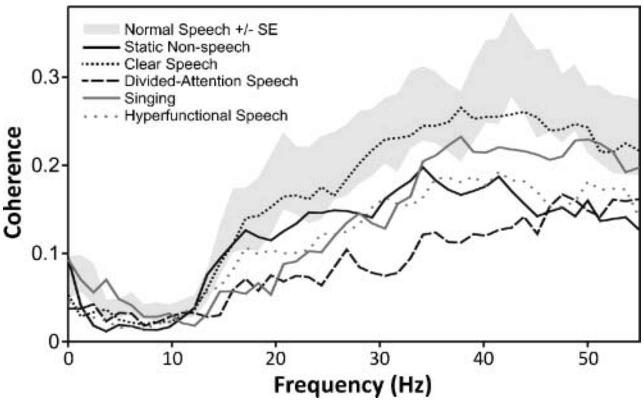
Two-factor ANOVAs were performed on both RMS measures by participant and condition. Pearson's product–moment correlations between NIBcoh and the RMS measures were calculated to assess whether gross sEMG activity or differences in overall energy between electrodes were factors in differences in NIBcoh. Of the 10 participants, individuals were further classified as singer or nonsinger on the basis of their reported singing experience (see Table 1). Two-sample two-tailed Wilcoxon–Mann–Whitney tests were performed on NIBcoh during normal speech and singing to assess the effect of singing background on NIBcoh.

Paired one-tailed Student's t tests were used to test the hypotheses that samples of speech using hyperfunctional voice had increased strain ratings over those produced using normal speech and that samples of clear speech had reduced mean syllable rate as compared with normal speech. Pearson's r was used to assess possible correlations between changes in strain ratings and changes in NIBcoh between hyperfunctional speech and normal speech.

Results

The mean anterior neck intermuscular coherence spectra for each condition are shown in Figure 2, presented relative to the mean ± standard error of the coherence spectra during normal speech production. Coherence was relatively high over beta frequencies for all conditions relative to the 5% significance values (<.04). However, clear differences in the magnitude of coherence were seen by condition across frequency. A two-factor ANOVA showed significant effects of both individual ($p < .001$) and condition ($p = .001$) on NIBcoh. Dunnett's simultaneous paired t tests between normal speech and other conditions found significantly decreased NIBcoh during low-attention speech, singing, and hyperfunctional speech relative to normal speech ($p_{\mathrm{adj}} < .05$). There was no significant difference in NIBcoh during static nonspeech

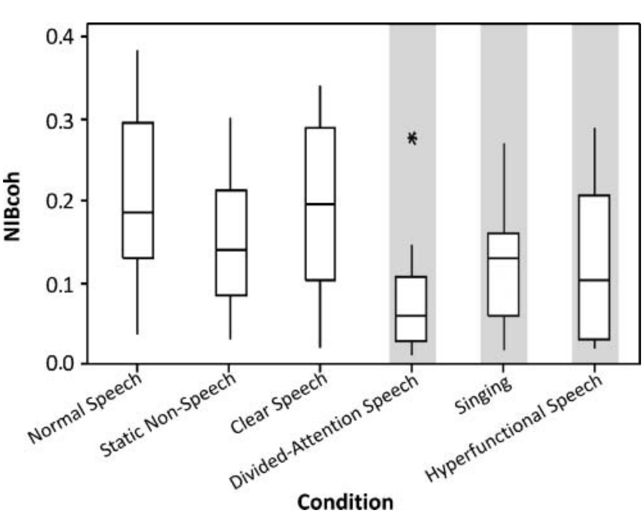
Figure 2. Mean anterior neck intermuscular coherence spectra by condition. The light gray shading indicates the mean coherence during normal speech ± the standard error by frequency.



tasks or clear speech production relative to normal speech production. Figure 3 shows boxplots of the mean NIBcoh for each condition.

Two-factor ANOVAs showed significant effects of both individual ($p < .001$) and condition ($p = .05$) on the mean-normalized RMS sEMG and a significant effect of individual ($p < .001$) for the difference in normalized RMS

Figure 3. Boxplots of the NIBcoh (neck intermuscular beta [15–35 Hz] coherence) by condition. Horizontal box lines indicate the lower and upper quartiles of the data, with the center line marking the data median. Vertical whiskers extend from the boxes to the minimum and maximum values of each data set. A two-factor analysis of variance showed significant effects of both individual ($p < .001$) and condition ($p = .001$) on NIBcoh. Dunnett's simultaneous paired *t* tests between normal speech and other conditions showed significantly decreased NIBcoh during divided-attention speech, singing, and hyperfunctional speech relative to normal speech ($p_{adj} < .05$), conditions that are highlighted in light gray. The asterisk shows a data point falling outside 1.5 times the interquartile range of the distribution.



between the two electrode locations. However, correlations between NIBcoh and the mean-normalized RMS sEMG and difference in normalized RMS sEMG between the two recording sites were $R^2 = .19$ and $R^2 = .08$, respectively.

Of the 10 participants, four individuals were further classified as singer and six as nonsinger based on their singing experience (see Table 1). Two-sample Wilcoxon–Mann–Whitney tests showed no difference between NIBcoh of "singers" versus "nonsingers" during normal speech or singing ($p > .05$). Table 1 also tabulates the NIBcoh of individuals during normal speech and singing.

The samples of the reading passage during normal speech had average CAPE-V strain ratings of 0.2 (SD = 0.6), whereas samples of the reading passage using hyperfunctional voice had average CAPE-V strain ratings of 45.1 (STD = 30.9). The average increase in CAPE-V strain rating was 44.9 (STD = 31.0), with a paired Student's *t* test showing a significant increase in strain during hyperfunctional speech relative to normal speech ($p < .001$). Changes in strain ratings between hyperfunctional and normal speech were not correlated with changes in NIBcoh ($R^2 < .001$). The samples of the reading passage during normal speech were produced at a mean rate of 4.4 syllables/second (STD = 0.5 syll/s), whereas samples during clear speech production were produced at a mean rate of 3.1 syll/s (STD = 0.6 syll/s). A paired Student's *t* test showed a significant decrease in the syllable production rate during clear speech relative to normal voice ($p < .001$).

Discussion

High NIBcoh During Speech Compared With Static Nonspeech Tasks

Past work in the upper limb has shown that intermuscular and corticomuscular coherence in the beta band is highest for static tasks and reduces upon movement onset (e.g., Kilner et al., 1999). Although we did not find a statistically significant difference, we unexpectedly found that static nonspeech tasks showed a trend of *decreased* NIBcoh relative to speech production.

One possible cause for the lack of NIBcoh for static nonspeech tasks could perhaps be the dependence of the NIBcoh measurement on overall available sEMG activity, which could be reduced in static conditions relative to active speech tasks. Although significant effects of both individual ($p < .001$) and condition ($p = .05$) were found on the mean-normalized RMS sEMG, the correlation between NIBcoh and mean-normalized RMS sEMG was relatively low ($R^2 = .19$). There must be sEMG activity present in recordings in order to find significant NIBcoh, but these data do not indicate that the overall signal strength was a primary determinant in the level of NIBcoh.

This finding is in apparent odds with previous work showing that for both low-level and moderate static force of the finger, corticomuscular coherence in the beta range increases with higher levels of force (Chakarov et al., 2009; Witte, Patino, Andrykiewicz, Hepp-Reymond, & Kristeva, 2007). However, these previous studies were limited to comparisons of static finger force production, whereas here we have compared across varied behaviors, making a strict comparison between these alternate findings ill-advised.

Some researchers have postulated a significance for high beta-band coherence in sensorimotor integration and motor learning (Perez, Lundbye-Jensen, & Nielsen, 2006; Witte et al., 2007). Although constant force production may elicit this behavior in the upper limb, it is possible that constant force activity from anterior neck muscles is too removed from their more natural and complex function for speech production, such that it does not require or promote energy in this band. It is further possible that NIBcoh is not indicative of beta-band oscillations as detected via corticomuscular and intermuscular coherence in the upper limb and that these oscillations of the neck musculature are indicative of a completely different physiologic phenomenon.

Effects of Attention on Speech-Related NIBcoh

Decreased NIBcoh was found during divided-attention speech relative to normal speech ($p_{\text{adj}} < .05$), matching well with the previous finding in the upper limb, in which coherence was reduced during divided task attention (Kristeva-Feige et al., 2002). However, although we hypothesized that production of clear speech might result in increased attention and precision, this condition did not result in increased mean coherence relative to normal speech despite significant slowing of syllable rate. One explanation for this finding is that the lack of increased coherence is due to a ceiling effect caused by the attention and precision most participants give to normal speech produced during an experimental recording. Future work to monitor coherence levels in normal and clear speech throughout prolonged testing may show evidence of adaptation to the experimental conditions, obviating this discrepancy.

Reduction of NIBcoh During Singing

For the 10 individuals studied, a decrease in NIBcoh during singing was found relative to normal speech production. One possibility is that the individuals tested have poor NIBcoh as a result of poor neural control over singing (e.g., poor singing ability) or that the singing task was anxiety provoking. However, when participants were separated into "singers' and "nonsingers" based on singing experience and training, no difference was found in NIBcoh during singing or normal speech (see Table 1). Ozdemir, Norton, and Schlaug (2006) found increased cortical activation in orofacial and possibly laryngeal areas of motor cortex during singing than during speech, which could possibly result in increased corticomuscular and motor cortex associated intermuscular coherence. However, a recent meta-analysis of studies of neural control of singing and speech has shown overall differences in the relevant neural networks (S. Brown et al., 2009), so differences in relevant oscillatory drives might be expected as well. The present findings do not directly address the neural bases of NIBcoh during singing, so further work using EEG or MEG and EMG during a variety of singing tasks should be done to better understand oscillatory drives underlying singing.

Possible Role of Anxiety

A confounding factor in this study is possible effects of task-related anxiety on NIBcoh during tasks. Given the findings of reduced NIBcoh in individuals with vocal nodules (a disorder associated with increased anxiety; e.g., Goldman, Hargrave, Hillman, Holmberg, & Gress, 1996), a role for anxiety in modulating NIBcoh is possible and worthy of further study. This potential factor may have manifested its effects in a variety of ways. First, the divided-attention task of counting backwards in increments of 7 was likely anxiety inducing for participants. Although the effect of anxiety on corticomuscular and intermuscular beta coherence has not yet been described, it is possible that increased anxiety rather than reduced attention is responsible for the deterioration of NIBcoh during the divided-attention task. Future work to determine the differential effects of anxiety and attention is warranted.

Furthermore, given the implications of beta-band coherence in sensorimotor integration and motor learning, the fixed order of task presentation in this study may have had an effect on the NIBcoh seen in the various tasks. Task-related anxiety could have been largest at the start of the experiment, leading to a decrease in NIBcoh during the first tasks relative to later tasks. This is a clear alternative explanation for the unexpected finding of high NIBcoh during speech compared with nonspeech tasks. The effect of experience throughout the experiment may have affected NIBcoh through adaptation and/or decreased anxiety. Future work using random presentation is necessary to unequivocally determine whether anxiety played a role in the present findings.

Reduction of NIBcoh During Hyperfunctional Voice

When participants mimicked hyperfunctional voice during speech production, significantly decreased NIBcoh was found relative to normal speech ($p_{adj} < .05$). The reduction in NIBcoh by individuals mimicking vocal hyperfunction is quantitatively and qualitatively similar to the lowered values of mean beta coherence seen previously in individuals with vocal nodules relative to individuals with normal voice (Stepp et al., 2010). Specifically, the mean NIBcoh for 18 participants with vocal nodules seen by Stepp et al. (2010) was 0.14 (SD = 0.13) and 0.26 (SD = 0.16) for 18 control participants. Likewise, the mean NIBcoh in the 10 individuals studied here during mimicked hyperfunctional voice was 0.12 (SD = 0.09), relative to 0.21 (SD = 0.11) during production of normal speech. This finding lends physiological support to the classification of vocal hyperfunction as a functional voice disorder, because individuals with typically normal voice were able to (unknowingly) modify their NIBcoh by mimicking hyperfunctional voice production. These findings are similar to those found in other movement disorders such as dystonia and tremor, in which analysis of intermuscular coherence and tremor frequency coherence have been successfully used to differentiate between the organic and psychogenic movement disorders (e.g., Grosse et al., 2004; McAuley & Rothwell, 2004).

Although significantly higher strain ratings were found for speech samples during hyperfunctional speech relative to normal speech, changes in strain ratings between hyperfunctional and normal voice were not correlated with changes in NIBcoh ($R^2 < .001$). This may suggest a lack of sensitivity in NIBcoh for degrees of vocal hyperfunction in voice production or a lack of tight correspondence between mimicked hyperfunctional vocal control and resulting vocal change. However, it might also be a result of the somewhat extreme levels of hyperfunction displayed by these individuals, or possible differences between mimicked hyperfunctional voice quality and the vocal hyperfunction associated with chronic abuse/misuse. Samples of the reading passage during hyperfunctional speech production had average strain ratings of 45.1, well within the moderate range of the CAPE-V (Kempster et al., 2009), whereas a study of 27 women with vocal nodules found mean strain ratings of only 18.3 (Menezes et al., 2010). Furthermore, even if the degree of strain in our participants was more like that seen in individuals with vocal hyperfunction, it is very possible that the physiological adjustments they used to mimic hyperfunctional voice may differ from the physiological configuration used by patients with vocal hyperfunction.

There is a need for relatively noninvasive objective clinical assays of vocal hyperfunction to allow for repeated assessment throughout the voice therapy process in order to identify progress. The present study combined with previous work in this area (Stepp et al., 2010) indicate promise for NIBcoh in this area; however, there are possible issues in the use of NIBcoh that must be studied before clinical adoption. The present work indicated a lack of sensitivity of NIBcoh to levels of perceived strain. Future work examining NIBcoh in trained, healthy normal individuals who are able to display multiple degrees of vocal hyperfunction is needed, as is longitudinal study of NIBcoh in patients with vocal hyperfunction throughout the vocal rehabilitation process. This will establish whether the lack of sensitivity in the present work is genuine or a result of the dissimilar nature of mimicked hyperfunction. Understanding how methodological factors such as electrode placement or type is also required to determine the accuracy and reliability of NIBcoh as a measure of vocal hyperfunction. Last, although much of the study of vocal hyperfunction has focused on identifying specific measures that may differentiate between disordered individuals and healthy controls, the clinical need goes beyond the capability to identify or diagnose vocal hyperfunction. Although NIBcoh was not explicitly studied here as a function of time, it was shown to vary considerably in a single session based on the particular task. Thus, the stability of this measure in typical speakers must be determined before applying it clinically as a measure of treatment change.

Summary

This work builds on the recent finding that individuals with vocal nodules show significantly lower NIBcoh than age- and gender-matched controls (Stepp et al., 2010), which suggests that NIBcoh during speech production might be an effective indicator of vocal hyperfunction for use as a clinical tool. The purpose of the present study was to better understand NIBcoh in healthy individuals, particularly with respect to modulation by behavioral tasks. As expected, NIBcoh was decreased in a divided-attention speech task; however, clear speech expected to be accompanied by increased attention and precision did not result in increased mean coherence relative to normal speech, possibly due to ceiling effects caused by the attention and precision given to normal speech produced during experimental recording. A reduction in NIBcoh during mimicking of vocal hyperfunction was seen that is quantitatively and qualitatively similar to the lowered NIBcoh seen in individuals with vocal nodules relative to individuals with normal voice. Future studies monitoring NIBcoh in vocal hyperfunction patients across the course of voice therapy are needed to determine whether this measure correlates with rehabilitative outcomes and to determine the sensitivity and specificity of this measure to different levels of vocal hyperfunction.

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