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Aerodynamic and Acoustic Features of Vocal Effort

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Abstract

Many voice disorders are associated with an effortful voice; however, there have been very few studies that have examined the physiological changes that contribute to this sense of effort. Determining the factors that contribute to change in vocal effort may help clinicians to effectively target these variables when working with people with voice disorders so that voice improvement is accompanied by decreased vocal effort after treatment. Prior research has shown that alterations in aerodynamic and acoustic variables are often associated with voice disorders involving increased muscular effort, and change in these variables is correlated with abnormal voice qualities. The current study focused on three main questions: 1) When producing speech with increased or decreased vocal effort as compared to comfortable vocal effort, how do healthy adults alter their phonatory physiology? 2) What are the acoustic manifestations of these changes in phonatory function that occur with high vocal effort? 3) Which aerodynamic or acoustic variables are the primary factors that are associated with an increase in vocal effort? The participants included 18 healthy men and women with normal voice and normal hearing, ranging in age from 18 to 26. After training, participants produced repeated syllable combinations at various levels of vocal effort (comfortable, maximal, and minimal). Aerodynamic and acoustic recordings were then analyzed. Three of the four aerodynamic measures in this study showed significant differences between the three vocal effort conditions, and reflected change in airflow, pressure, and rate of airflow change during voice production. Both acoustic measures, which related to the relative degree of harmonic energy in the speech signal also showed significant differences between the three vocal effort conditions.

AERODYNAMIC AND ACOUSTIC FEATURES OF VOCAL EFFORT

by

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Introduction

Importance of Vocal Effort in Voice Disorders

Effortful voice production is a critical component of many voice disorders, yet the physiology that contributes to this sense of effort has been minimally studied. Vocal effort is often perceived by others as a strained voice quality (Kempster, Gerratt, Verdolini Abbott, Barkmeier-Kraemer, & Hillman, 2009), and is considered to be a component of vocal hyperfunction, which involves increased activity of muscles in and around the larynx (Boone, McFarlane, Von Berg, & Zraick, 2010). Hyperfunctional voice disorders with strained voice quality are characterized by increased compression of the true vocal folds (Askenfelt & Hammarberg, 1986), increased constriction of structures directly above the level of the vocal folds (Morrison, Nichol, & Rammage, 1986; Stager, Bielamowicz, Regnell, Gupta, & Barkmeier, 2000), and increased supralaryngeal muscle activation (Hocevar-Boltezar, Janko, & Zargi, 1998). Therefore, the increased vocal effort that occurs in hyperfunctional voice disorders can be associated with a number of physiological states, such as altered patterns of intrinsic and extrinsic laryngeal muscle activation, attempts to compensate for a lack of vocal fold closure, altered respiratory behavior, or other changes in the vibratory patterns of the vocal folds. Because of the multiple physiological contributions that can produce increased vocal effort, the quality of strain is evidenced across a variety of voice disorders.

Non-organic, organic, and neurological voice disorders can alter closure patterns or muscle activation patterns during vocal fold vibration, with subsequent perceptual consequences of strained voice quality and increased vocal effort. In muscle tension dysphonia, this increased vocal effort is associated with an over-activation and imbalance of musculature in and around the larynx (Altman, Atkinson, & Lazarus, 2005; Hocevar-Boltezar, et al., 1998; Roy, 2003; Van

Houtte, Van Lierde, & Claeys, 2011), and is considered a contributing factor to the disorder (Boone, et al., 2010). In disorders such as vocal nodules, habitual vocal hyperfunction contributes to the development of a lesion. The presence of the tissue mass associated with the lesion causes incomplete closure of the vocal folds, which can lead to a further increase in vocal effort as the patient attempts to improve adduction. Likewise, other disorders such as vocal polyps and papilloma that create mass lesions on the vocal folds can result in compensatory hyperfunction in an effort to increase vibratory closure. In neurological voice disorders such as adductor spasmodic dysphonia, substantially increased vocal effort is a primary feature of the disorder that is related to involuntary, adductor spasms of intrinsic laryngeal muscles. In contrast, the neurological disorder of unilateral vocal fold paralysis can be associated with compensatory hyperfunction as the patient attempts to compensate for inadequate vocal fold closure by over-activating muscles in surrounding regions associated with laryngeal constriction.

Effective treatment of voice disorders requires addressing any structural or neurologic abnormalities affecting the larynx, and then reducing the hyperfunctional laryngeal behaviors that are directly associated with the disorder or that arose as a compensatory response. Goals for treating hyperfunctional voice disorders are directed toward achieving optimal voice quality and vocal function while developing phonatory behaviors that are associated with a minimal sense of effort (Boone, et al., 2010). Outcome data for treatment efficacy often include an assessment of change in self-perceived effort from pre- to post-treatment time points (Colton, Casper, & Leonard, 2011; Verdolini-Marston, Burke, Lessac, Glaze, & Caldwell, 1995). By determining the physiologic changes that contribute to increased vocal effort, treatment approaches can be tailored to modify specific phonatory behaviors with the goal of minimizing vocal effort. Studying the effects of systematic changes in vocal effort on phonatory behavior is difficult in people with voice disorders because they present with chronically increased vocal effort and are therefore unable to vary that effort between minimal, comfortable, and maximal levels. Instead, by focusing on healthy individuals without voice disorders, we can determine the critical components of phonatory function that differentiate voice produced with maximal or minimal vocal effort from that produced at a comfortable level of effort.

Physiology Associated with Sense of Effort

Changes in vocal fold compression and laryngeal muscle activity during phonation are thought to produce the perceptual outcomes of increased vocal effort and strain, yet little is known about the relative contributions of laryngeal physiologic variables to vocal effort. The larynx is equipped with rich sensory innervations, providing multiple forms of sensory information that can be associated with increased vocal effort. In humans and related mammalian species, laryngeal sensory nerve fibers are extensively represented between the top of the epiglottis and the first tracheal ring, combining into the sensory branches of the recurrent laryngeal nerve and the internal branch of the superior laryngeal nerve (Mu & Sanders, 2000; Yoshida, Tanaka, Hirano, & Nakashima, 2000). Tremendous variety in types of laryngeal receptors is evidenced, including those responsive to light and deep touch and those responsive to low and high frequency vibratory stimulation (Davis & Nail, 1987). Highly specialized chemoreceptors provide additional forms of sensory input in the laryngeal region (Yoshida, et al., 2000). Rapid changes in laryngeal muscle activation occur with air pressure stimulation to the laryngeal mucosa (Aviv, 1997; Aviv et al., 1999; Bhabu, Poletto, Mann, Bielamowicz, & Ludlow, 2003). Thus, subtle changes in laryngeal pressure, airflow and laryngeal constriction can all provide sensory feedback related to vocal effort.

In human physiology studies, sense of effort is thought to be associated with copies of motor output commands that get routed to sensory areas of the cortex, which then interpret increased muscle activation as a sense of increased effort (Cafarelli, 1982; Jones, 1995). At the peripheral level, receptors within muscles and tendons contribute to our sense of force by indicating level of tension exerted on the muscle (Jones, 1995). Therefore, degree of tension and muscle contraction of the larynx is likely to contribute to the sense of vocal effort. Sense of effort shows linear increases with various physiologically imposed muscle loads (Cafarelli, 1982), including respiratory load (Supinski, Clary, Bark, & Kelsen, 1987), lingual resistance (Somodi, Robin, & Luschei, 1995), and vocal load (Chang & Karnell, 2004). When healthy adults are asked to produce speech before and after a vocally fatiguing task, the threshold pressure that is needed from the lungs to initiate vocal fold vibration (Titze, 1988) systematically increases with ratings of vocal effort (Chang & Karnell, 2004; Solomon & DiMattia, 2000; Solomon, Glaze, Arnold, & van Mersbergen, 2003). Taken together, these studies indicate that variations in sense of effort are directly associated with physiologic changes in performance of a motor task such as speech.

Aerodynamic Indicators of Phonatory Function and Voice Quality

Hyperfunctional voice can be differentiated from normal voice by using noninvasive aerodynamic measures (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989). Aerodynamic measures such as translaryngeal airflow, subglottal pressure, and translaryngeal resistance provide direct indicators of laryngeal physiology. When phonation is produced with increased constriction of the vocal folds and surrounding regions, airflow through the vocal folds is reduced, air pressure just below the vocal folds (subglottal pressure) is increased, and translaryngeal resistance (laryngeal pressure divided by laryngeal airflow) is increased relative to phonation produced during normal voice without undue constriction. The pneumotachometer instrumentation system allows for measurement of oral airflow and pressure, which during certain consonant-vowel sequences can be used as to derive valid estimates of translaryngeal airflow, subglottal pressure, and associated translaryngeal resistance (Rothenberg, 1982; Smitheran & Hixon, 1981). Use of additional specialized masks with a pneumotachometer system and associated software can provide data on the estimated airflow signal at the level of the vocal folds (glottal airflow), without the modulatory effects of the upper vocal tract (Rothenberg, 1973).

One useful measure drawn from this unmodulated airflow signal is the maximum flow declination rate (MFDR), which reflects the speed at which the airflow decreases in the closing phase of vocal fold vibration and is associated with how rapidly the vocal folds are closing. Speed of vocal fold closure is associated with greater amplitude of vibration, and can be elevated in people with hyperfunctional voice disorders (Hillman, et al., 1989, 1990). MFDR has also been found to be strongly related to vocal effort (Holmberg, et al., 1988; Hillman, et al., 1989, 1990).

Another non-invasive tool for determining laryngeal function is electroglottography (EGG). EGG indicates the amount of vocal fold contact by showing changes in resistance to the flow of small, high frequency electrical current that is passed through the neck at the level of the larynx. Varying degrees of laryngeal constriction can be determined by analyzing the length of time that the vocal folds are closing or closed relative to the duration of vocal fold opening (closed quotient).

Hillman and colleagues have presented a theoretical model for vocal hyperfunction, suggesting that changes in laryngeal configuration are associated with either adducted or non-adducted hyperfunction (Hillman, et al., 1989, 1990). These authors suggest that individuals who over-adduct the vocal folds during vibration will be predisposed to damaging the delicate vocal fold tissue, whereas people with non-adducted hyperfunction will show generalized tension of the vocal folds during vibration and will experience vocal fatigue without increased likelihood for tissue pathology. Data from small subgroups of voice-disordered patients showed that in people with adducted hyperfunction, decreased glottal airflow, increased subglottal pressure and high maximum flow declination rates were evidenced in comparison to other voice disorder types, indicating greater speed of closure and vocal fold collision forces (Hillman, et al., 1989, 1990). In the current study, it was expected that changes in vocal effort might be associated with either over- or under-adduction of the vocal folds. Translaryngeal resistance can help determine which pattern is used when normal participants increase their effort level.

Voice quality differences along the continuum of breathy to pressed reflect changes in laryngeal adduction. Peterson and colleagues (Peterson, et al., 1994) studied the effects of systematic variation in voice quality on aerodynamic and laryngeal configuration measures. Aerodynamic measures were assessed with a pneumotachometer and included MFDR and laryngeal airflow, whereas laryngeal configuration was assessed using the closed quotient from EGG analysis. Seven healthy adults who previously received voice training were studied during productions of the vowels /a/, /i/, and /u/. After modeling and training, participants produced each vowel using four voice quality variants: pressed, resonant, normal, and breathy quality. Ratings of videostroboscopic images of the larynx were used to determine degree of laryngeal adduction during each voice quality type. Pressed voice quality showed significantly higher ratings of laryngeal adduction than the other voice quality types, and breathy voice quality showed significantly lower ratings of adduction than either resonant or normal voice quality.

Closed quotient EGG values were strongly correlated with laryngeal adduction ratings, and significantly differentiated the voice quality types. In contrast, aerodynamic measures did not significantly distinguish the voice qualities. MFDR showed trends toward highest values for pressed voice and lowest values for breathy voice, although resonant voice also showed higher MFDR values. Lack of differentiation of voice quality types by aerodynamic measures may have been impacted by low power associated with small sample size (7 participants).

Translaryngeal resistance can provide a sensitive aerodynamic indicator of the phonatory function differences that occur with varying voice qualities. Grillo and Verdolini (2008) studied 13 women with vocal expertise to determine if translaryngeal resistance and/or vocal efficiency could distinguish between a pressed, normal, resonant, or breathy voice. Vocal efficiency is a relational measure that shows how well the vocal folds and the respiratory system are functioning together. Translaryngeal resistance reliably distinguished between a pressed, normal, and breathy voice. Translaryngeal resistance was also measured during resonant voice production, in which participants produced voice with an easy phonation and with vibration on the alveolar ridge. No differences in translaryngeal resistance were evidenced between the normal and resonant voice tasks. The authors noted that because the participants had vocal expertise, their normal voices may have been produced with resonant voice quality, explaining the lack of translaryngeal resistance differences between these two speaking tasks. Vocal efficiency did not consistently distinguish the four vocal qualities studied. The results of this study support the utility of the measure of translaryngeal resistance for indicating variations in voice quality that may be associated with systematic changes in sense of vocal effort.

Ratings of voice quality by external listeners also correspond with systematic changes in aerodynamic measures. Netsell, Lotz, & Shaughnessy (1984) determined the relationship between subglottal air pressure and laryngeal air flow in 18 participants with mixed voice disorders and 30 normal speakers to gain insight regarding laryngeal dysfunction. During a sustained /a/ and repeated syllable /pa/, subglottal air pressure and laryngeal airflow were measured. Results indicated that participants with normal subglottal pressure and high glottal airflow were consistently rated by external listeners as having a breathy voice quality. Participants with high subglottal air pressure and low airflow values were perceived to have a strained voice quality. Netsell and colleagues hypothesized that patterns of high airflow, normal subglottic pressure and perceived breathiness were associated with insufficient vocal fold adduction; whereas patterns of increased subglottic pressure, decreased glottal airflow and perceived strain were indicative of hyperadducted vocal folds. These authors also suggested that some participants with voice disorders compensate for reduced vocal fold adduction by increasing subglottic pressure, which produces increased airflow and perceived roughness in voice quality.

Relationships Between Acoustic, Aerodynamic, and Perceptual Features of Voice

Changes in the acoustic features of the speech waveform can also be associated with physiologic changes in vibratory behavior of the vocal folds, and are often related to aerodynamic changes. Plant (2005) simultaneously measured aerodynamic and acoustic features of voice in six healthy participants who produced multiple sustained /i/ vowels. Acoustic measures of fundamental frequency and sound intensity were simultaneously acquired with the aerodynamic measures of laryngeal airflow and subglottal pressure. The participants were asked to produce the vowel at a range of different pitches and intensities. Fundamental frequency and intensity increased in a generally linear fashion as subglottal pressure increased. However, the authors noted that there was substantial variation in the degree, or slope of those changes between participants. Rapid variations in subglottic pressure were seen for vocal fold vibration onset and offset, supporting the use of subglottic pressure as a reflection of vibratory patterns. In a previous study (Plant & Younger, 2000), a linear relationship between subglottic pressure and intensity during consonant-vowel sequences (/pa/) as well as /i/ vowel repetitions was demonstrated in nine healthy subjects who produced voice at varying levels of intensity.

Acoustic analysis in voice disorders has moved toward the use of spectral and cepstral-based measures, which are derived from the spectral distribution of sound energy and do not rely on a time-based analysis of the acoustic waveform. Performing a Fourier-transform on the spectrum produces the cepstrum, which demonstrates peaks of harmonic energy in the signal. Cepstral peak prominence (CPP) indicates the degree to which the dominant energy peak (often attributed to the fundamental frequency) is distinguished from the background noise level of the overall signal. Current research shows that CPP and the standard deviation of CPP are some of the strongest predictors of auditory-perceptual voice severity (Awan & Roy, 2005, 2009; Awan, Roy, & Dromey, 2009; Eadie & Baylor, 2006) and provide excellent discrimination of normal versus dysphonic voice (Awan & Roy, 2005; Eadie & Doyle, 2005). In a recent study addressing the acoustic features of dysphonic voices characterized predominantly by strain, cepstral-based measures were the strongest predictors of auditory-perceptual strain severity, with CPP and its standard deviation showing correlations of greater than 0.80 to perceptually rated strain severity (Lowell, Kelley, Awan, Colton, & Chan, 2012). The strong relationships that various acoustic measures show with aerodynamic and perceptual features of voice support the use of acoustic measures to reflect underlying vocal behavior, and indicate that both aerodynamic and acoustic measures are essential to consider when studying the physiological bases for effortful voice production.

Speaker Reliability in Producing and Rating Vocal Effort

To study the aerodynamic and acoustic outcomes of vocal effort, it is ideal to systematically vary level of effort and then measure the associated changes. Individuals with voice disorders are unable to produce varying levels of vocal effort or strain because reducing that effort and strain usually requires therapeutic intervention. Healthy adults without voice disorders can be trained to produce varying levels of vocal effort (Chang & Karnell, 2004). Furthermore, normal speakers can reliably produce variations in level of vocal effort, and can reliably rate that level of effort (Colton, 1973; Wright & Colton, 1972). When asked to produce the vowel /a/ at maximum, minimum, and comfortable levels of effort, speakers showed systematic changes in intraoral pressure and fundamental frequency, indicating their ability to reliably estimate and produce variations in effort along a continuum.

Brandt, Ruder, & Shipp (1969) investigated differences between loudness and vocal effort while participants produced speech in three ways: with changes in loudness and vocal effort, with loudness held constant and vocal effort varied, and with vocal effort held constant while loudness was varied. Listeners then rated both loudness and degree of vocal effort. Based on study results, the authors suggested that vocal loudness and vocal effort are perceived differently by listeners. These findings indicate that while sound pressure level (SPL) and vocal effort can be related, other factors are important to listeners' perception of increased vocal effort in speech.

Current Study

To understand the physiology that contributes to vocal effort and strained voice quality, it is important to systematically vary the degree of vocal effort during speech and determine the aerodynamic and acoustic consequences. Determining the physiologic variables that are predominantly used by healthy individuals when increasing their degree of vocal effort may improve our clinical understanding of which physiologic variables are crucial to target in voice therapy to decrease level of speaking effort in people with voice disorders. By directly manipulating level of vocal effort, the corresponding changes in aerodynamics and acoustics can be determined.

This study addressed the following questions: 1) When producing speech with increased or decreased levels of vocal effort as compared to comfortable vocal effort, how do healthy adults alter their phonatory physiology? 2) What are the acoustic manifestations of these changes in phonatory function that occur with high vocal effort? 3) Which aerodynamic or acoustic variables are the primary factors that are associated with an increase in vocal effort?

Method

Participants

This study was approved by the Institutional Review Board (IRB) at Syracuse University, and all participants provided informed consent and were paid for their participation. Participants were recruited from the university community through the use of IRB approved flyers and email postings. Eighteen participants (12 female, 6 male) were included in this study who met the following criteria: a) were healthy per self-report, b) had no reported history of neurological or other medical disease that could affect speech, c) had no reported laryngeal pathology or voice disorder, d) used English as their primary language, and e) were between the ages of 18 and 26, representing a younger adult population that has been previously studied (Grillo & Verdolini, 2008). Participants in older age ranges may experience changes to laryngeal structure or physiology and therefore were not included. As determined through a hearing screening, participants demonstrated adequate hearing of 25 dB HL or better at 500, 1000, 2000 Hz

(Higgins, Chait, & Schulte, 1999), to control for possible effects on speech that have been documented for severe to profound hearing loss (Forner & Hixon, 1977; Lane, Perkell, Svirsky, & Webster, 1991). As determined from a phone screening, participants demonstrated perceptually normal voice, with no detectable accented speech.

Based on translaryngeal resistance data from a prior study that measured the aerodynamic effects of pressed, normal, resonant and breathy voice quality (Grillo & Verdolini, 2008), an effect size of 5.48 was determined for the comparison of pressed voice to the least contrastive condition. Using this effect size, a minimum sample size of six was determined with a power of 0.80 and a p value of .0125 (corrected for multiple comparisons). We expected that our aerodynamic values would show less differences between conditions for variations in vocal effort as compared to the variations in voice quality that were required by Grillo and Verdolini (2008). Consequently, 18 participants were included for greater statistical power potential. Research addressing voice disorders related to vocal hyperfunction indicates that females more frequently present with these disorders than males. In several studies addressing the characteristics and treatment of muscle tension dysphonia, a disorder characterized by vocal hyperfunction, females represented between ~67% (Rubin, Blake, & Mathieson, 2007) and ~80% (Lowell, Kelley, Colton, Smith, & Portnoy, 2012; Mathieson et al., 2009; Roy, Whitchurch, Merrill, Houtz, & Smith, 2008) of the sample population. Our final gender distribution approximated that for hyperfunctional voice disorders, with 67% female and 33% male.

Screenings

An initial phone screening was performed with each participant who indicated an interest in participating in the study. The phone screening was used to determine basic eligibility and to verify that overall voice quality was within normal limits. After initial qualification, each participant was subsequently seen for a voice screening. Voice recordings of sentence level speech were performed in a sound-attenuated booth, using a condenser, head mounted microphone at a distance of 15 cm from the mouth. The Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V), a standardized and validated auditory-perceptual ratio scale that includes the assessment of overall dysphonia severity and several individual voice quality characteristics, was used for the sentence stimuli and subsequent perceptual ratings by listeners (Kempster et al., 2009). Recordings were used to obtain average fundamental frequency (F_0) levels for each speaker. The Computerized Speech Lab (KayPENTAX, CSL 4500) was used to acquire and analyze all acoustic signals, with a sampling rate of 50 kHz.

Ratings of Perceived Speaking Effort and Voice Quality

Participants produced the syllable sequence /pi/ (e.g., pi pi pi pi pi pi pi) at varying levels of vocal effort. Because speakers can capitalize on proprioceptive cues from the respiratory, laryngeal, and articulatory systems in addition to auditory feedback during self-productions, each participant was considered the optimal judge of perceptual vocal effort for their own productions. Participants were asked to produce syllable sequences at varying levels of vocal effort. Vocal effort was defined to participants as the perceived amount of effort that it takes to produce each syllable sequence (Chang & Karnell, 2004; Solomon, et al., 2003), while noting that vocal effort may be associated with multiple areas of the body that contribute to speech production. See Appendix A for specific instructions and experimenter procedures that were given to participants. In an initial training task, participants produced the syllable sequence at a comfortable level of vocal effort, a maximal level of vocal effort, and a minimal level of vocal effort. Directly after producing each syllable sequence, participants assigned a numeric value to each production to provide a direct magnitude estimation of vocal effort for each production (Colton, 1973; Wright & Colton, 1972). After the training was completed, participants also provided numeric estimates for each of their syllable sequences during the aerodynamic measurements described below.

To provide an external measure of the voice quality associated with each syllable sequence, one listener who was blinded to speaking task type performed ratings of all the speech samples for the degree of vocal strain and breathiness using the CAPE-V 100mm visual analog scale. This visual analog scale has descriptors of mild, moderate, and severe to orient the listener, which are written below the 100mm line and spaced at equal intervals. The listener performed ratings of the syllable sequences that were analyzed for the aerodynamics for each speaking task, with all samples presented in randomized order. The listener was given the same CAPE-V definition of strain and breathiness as described in the CAPE-V (Kempster, et al., 2009). To improve reliability of ratings, anchor samples (non-experimental exemplars from voice disordered speakers) with exemplars of mild, moderate and severe levels of breathiness and strain were used during the ratings. One or more anchor samples were played for comparison with each experimental sample that was rated.

Speaking Tasks and Aerodynamic Measurement

For the experimental tasks, participants produced the repeated syllable sequence of the /pi/ consonant-vowel utterance at varying degrees of vocal effort, with the same instructions as were provided in the initial training of these tasks. Sequences of five to seven syllables, at a rate of 1.5 syllables/sec., were trained and then elicited for all productions based on the requirements for the aerodynamic measurements (Smitheran & Hixon, 1981). This speaking rate allowed for accurate measurement of oral and air pressure and airflow while promoting the tight velopharyngeal closure that is necessary for adequate buildup of oral pressure. To elicit productions at a comfortable pitch level that represents modal register for each participant, productions were elicited at +/- 15% of the participant's mean F_0 as measured during the CAPE-V sentences from the voice screening. A real-time visual display of their F_0 on a laptop computer was used to verify correct F_0 range. An audio sample of the participant's own voice at the target pitch level was played for participant prior to eliciting their syllable productions.

Using the Glottal Enterprises MS100-A2 with MCU-4 Calibration Unit, recordings of oral airflow and pressure were obtained to derive estimates of subglottal pressure and translaryngeal airflow. Figure 1 illustrates the instrumentation used for signal acquisition. Airflow and pressure were calibrated prior to each participant session. A vented Rothenberg mask with oral tubing and a pressure transducer was placed securely over the nose and mouth of each participant. A low-pass filter was used on the pressure signal at 10Hz to optimally represent and isolate changes in pressure from the recorded signal. A multichannel, digital acquisition hardware and TF32 software system was used to display, record, and analyze the airflow and pressure signals. Syllable sequences were monitored throughout recording sessions to verify continuous phonation and stable pressure peaks. Syllable sequences at each of the three varying levels of vocal effort were then elicited with at least three repetitions of each production. Speech tasks produced at maximum and minimum levels of vocal effort were elicited in counter-balanced order across participants to control for order effects. The comfortable vocal effort task was always elicited first so that participants could subsequently maximize or minimize their vocal effort relative to what was comfortable for them. Experimenters verbally instructed the participant for each syllable sequence as to which level of effort should be produced.

A desktop, condenser microphone within a Tascam DR-2d Linear PCM Recorder was placed ~14 inches from the speaker's mouth to simultaneously record the acoustic signal for subsequent acoustic analysis at a sampling rate of 50 kHz. To monitor and record sound pressure level (SPL), a calibrated sound level meter with a condenser microphone was used throughout all sessions. This microphone was placed at a standard distance of 18 inches from the speaker's mouth, and microphone input was routed to both the sound level meter and the multichannel recording system. Thus, simultaneous acoustic and aerodynamic data was obtained so that audio signals could be used to assist the aerodynamic analysis. The digital audio recordings from the Tascam DR-2D recorder provided high quality audio recordings that could then be analyzed to determine the acoustic outcomes of varying levels of vocal effort, and their relationship to aerodynamic measures. Detailed participant instructions and experimenter procedures are provided in Appendix A.

Dependent Measures and Descriptive Analyses

To address study question 1) regarding the changes in phonatory function that were used to produce increased vocal effort, four dependent measures from the aerodynamic data were analyzed: subglottal pressure, translaryngeal airflow, translaryngeal resistance, and maximum flow declination rate (MFDR). Translaryngeal resistance provided an indicator of the degree of laryngeal constriction that occured during voice production and was determined by dividing subglottal pressure by translaryngeal airflow. Because translaryngeal resistance can be elevated due to high subglottal pressure or low translaryngeal airflow, it is important to also determine the separate contributions of each measure to translaryngeal resistance. MFDR provided an indication of the speed of closure of the vocal folds, and elevated MFDR can be associated with vocal hyperfunction (Hillman, et al., 1989, 1990). Syllables were selected for analysis of pressure and airflow if they showed consecutive pressure peaks were within 0.5 cmH_2O of each other. When possible, utterances that the participant rated highest for vocal effort (in the maximal effort task) or lowest for vocal effort (in the minimal vocal effort task) were used for the aerodynamic analyses. Three pressure values and associated mean translaryngeal airflow values were analyzed for each participant and each speaking task, and then a mean value for each measure was determined from the three data points. To address study question 2) regarding the acoustic manifestations of increased vocal effort, a cepstral analysis was performed on the acoustic signal. Based on the results of a previous study that indicated the acoustic measures of cepstral peak prominence (CPP) and CPP standard deviation (CPP sd) were the primary acoustic factors related to strained voice quality (Lowell et al., 2012), these measures were derived from syllable productions and measured in decibels to determine the acoustic manifestations of vocal effort. To address study question 3) regarding which aerodynamic or acoustic factors primarily contribute to increased vocal effort, we analyzed the effect sizes for each of the statistical task comparisons.

Auditory-perceptual ratings of voice qualities of strain and breathiness were obtained for descriptive purposes to determine any changes in voice quality that were associated with varying vocal effort. An experienced listener performed the ratings of breathiness and strain (measured on the CAPE-V visual analog scale) to provide descriptive data regarding the auditory-perceptual consequences of increased vocal effort, and to relate perceptual data to vocal function data. The audio samples were equalized for SPL, randomized, and then rated by a blinded listener. SPL was equalized to avoid the potential biasing effects of sound intensity when the rater performed auditory perceptual judgments. To determine the intra-rater reliability of the consensus auditory-perceptual ratings, approximately 20% of audio samples with inclusion of each speaking task were randomly intermixed into the audio samples for repeat assessment during the perceptual ratings. A Spearman's rho correlation coefficient was used to determine intra-rater reliability because of the non-normal distribution of the CAPE-V data. The correlation coefficient of 0.785, $p < 0.001$, indicated sufficient intra-rater reliability for the auditory-perceptual ratings. The acoustic measures of F_0 and intensity were also determined for each syllable sequence to describe any changes in these variables that are associated with increased vocal effort.

Statistical Analysis

To address study question 1), repeated analysis of variance (ANOVA) was used to test which of the four aerodynamic variables showed significant differences between the three speaking tasks produced at varying levels of vocal effort. Significance level was defined at 0.0125 to correct for multiple comparisons. Follow-up contrasts with two-tailed *t*-tests were used to determine which comparisons were significant. To address study question 2), repeated analysis of variance (ANOVA) was used to test for which of the two acoustic variables show significant differences between the three speaking tasks produced at varying levels of vocal effort. Significance level was defined at 0.025 to correct for multiple comparisons. Follow-up contrasts with two-tailed *t*-tests were used to determine which comparisons were significant. For the measures that showed non-normal distributions, non-parametric equivalent tests for three or more repeated measures (Friedman test) and for paired comparisons (Wilcoxon Signed Rank test) were used to determine significant differences. To address study question 3), the effect sizes were determined for each paired task comparison of the aerodynamic and acoustic measures that showed significant overall task differences.

Possible gender differences in the mean values for each aerodynamic and acoustic measures were determined using gender as a between-group variable in repeated measure

ANOVAs for each dependent variable. To determine the relationships between SPL and the aerodynamic variables, Pearson product correlation coefficients were computed.

Results

Aerodynamics

All four aerodynamic measures exhibited significant differences between the three speaking conditions (comfortable, maximal, and minimal vocal effort). Means and standard deviations for all aerodynamic measures are shown in Appendix B, Table 1. The overall repeated measures ANOVA for translaryngeal airflow showed significant differences across tasks, $F(2, 34) = 8.9$, $p = 0.001$, with normally distributed data for this measure. Subglottal pressure, translaryngeal resistance and MFDR showed non-normal distributions, and task differences were therefore assessed with the non-parametric statistical equivalent for repeated measures ANOVA, the Friedman test for related samples. Significant, overall differences across tasks were evidenced for subglottal pressure, $p < 0.001$, MFDR, $p < 0.001$, and translaryngeal resistance ($p = 0.006$). For a graphic demonstration of scores across tasks see Figures 2, 3, 4, and 5.

Follow-up contrasts were performed using paired-sample *t*-tests or Wilcoxon Signed Rank tests for related samples (non-parametric equivalent) for each variable that showed significant overall task differences as described above. These contrasts addressed the comparisons of interest for this study: which aerodynamic variables showed significant differences when participants produced increased (maximal) or decreased (minimal) vocal effort as compared to comfortable (typical) vocal effort. Table 3 summarizes the *t*-test and Wilcoxon Signed Rank test results and effect sizes for each paired comparison. Subglottal pressure showed significant differences for both maximal and minimal vocal effort as compared to comfortable effort, with similar effect sizes for both comparisons. Translaryngeal airflow also showed significant differences for the comparisons of comfortable to maximal and comfortable to minimal vocal effort, with stronger differences for the comfortable to maximal comparison (Cohen's $d = 0.96$) than for the comfortable to minimal effort comparison (Cohen's $d = 0.56$). MFDR also showed significant differences for both task comparisons, with the strongest differences evidenced for the comfortable to maximal comparison (Cohen's $d = 0.81$) versus the comfortable to minimal effort comparison (Cohen's $d = 0.57$). Finally, laryngeal resistance showed a significant difference for the comparisons of comfortable to minimal levels of vocal effort (Cohen's $d = 0.62$).

The gender distribution in our healthy participant group (6 males, 12 females) was representative of the gender ratios that are evidenced with most voice disorders (more females than males). However, to determine whether there were gender-specific effects that may have accounted for the task differences, we performed between-group analyses with repeated-measures ANOVAs for each of the dependent variables. The only measure that showed a significant differences between male and female participants was MFDR, $F(1, 16) = 8.1$, $p = 0.012$). Male MFDR mean values were higher than women for all three tasks.

Acoustics

Both acoustic measures that were assessed in this study showed significant differences between the varying levels of vocal effort, with normally distributed data for each measure and task. Table 2 displays the means and standard deviations for both measures. The overall repeated measures ANOVAs showed significant differences across tasks for CPP, $F(1, 24) = 11.6$, $p = 0.001$ (Greenhouse-Geiser correction), and for CPP sd, $F(2, 34) = 6.7$, $p = 0.003$. Gender effects were also analyzed for the acoustic variables using gender as a between-subjects factor in the overall repeated measures ANOVAs. Both acoustic variables showed significant differences between the results for men versus women (for CPP, $p = 0.012$, for CPP sd, $p = 0.012$). Male CPP and CPP sd mean values were higher than women for most of the tasks. For comparison of scores across task see Figures 6 and 7.

Follow-up contrasts with paired-sample *t*-tests were performed for both acoustic variables (Table 4). For CPP, the comparison of comfortable and maximal vocal effort showed significant differences, with a moderate strength of effect (Cohen's $d = 0.52$). CPP mean values were higher for the maximal vocal effort task as compared to comfortable effort. The comparison between comfortable and minimal vocal effort was non-significant. For CPP sd the comparison between comfortable and minimal vocal effort showed significantly higher mean values for the comfortable vocal effort task (Cohen's $d = 0.51$), with no significant differences for the comparison of the comfortable to maximal vocal effort tasks.

Subjective Ratings

Participants in the study were asked to rate their level of perceived vocal effort for each production. Although free to use their own metric, all participants chose values between 1 and 10 for their ratings. When producing a comfortable vocal effort, participants rated their productions at an average of 4.04 (sd = 1.44). Maximal vocal effort was rated as higher for all participants, with an average rating of 7.46 (sd = 1.45). Minimal vocal effort was rated the lowest, with an average of 1.87 (sd = 0.83) across participants.

Auditory-perceptual ratings of voice quality were performed to determine whether changes in voice quality accompanied changes in vocal effort. The comfortable vocal effort task showed mean ratings for *strain* of 1.56 mm (on a visual analog scale of 0-100 mm), with an sd of 2.15 mm. The maximal vocal effort task showed mean ratings for strain of 6.14 mm (sd = 8.49 mm). The minimal vocal effort task showed mean ratings for strain of 0.53 mm (sd = 3.04 mm).

For the voice quality of *breathiness*, the comfortable vocal effort task showed mean ratings of 5.22 mm (sd = 7.71 mm). The maximal vocal effort task showed mean ratings for breathiness of 0.86 mm (sd = 1.29 mm). The minimal vocal effort task showed mean ratings for breathiness of 6.06 mm (sd = 9.92 mm).

Correlations

Each dependent variable was compared against the average SPL for each condition to determine if a change in SPL was correlated with the change in the variable. For the comfortable vocal effort task, MFDR ($r = 0.535$, $p = 0.022$) and CPP sd ($r = 0.491$, $p = 0.039$) both showed moderate, significant correlations with SPL. For the maximal vocal effort task, translaryngeal airflow ($r = 0.550$, $p = 0.018$), MFDR ($r = 0.657$, $p = 0.003$) and CPP sd ($r = 0.509$, $p = 0.031$) showed moderate or higher, significant correlations with SPL. For the minimal vocal effort task, SPL was not significantly correlated to any of the dependent variables.

Gender differences were also reviewed for sound pressure level (SPL). During a comfortable level of vocal effort, male participants had an average of 70.3 dB SPL (sd=3.32), while female participants had an average of 66.2 dB SPL (sd=4.04). For maximal vocal effort, males had an average of 76.0 dB SPL (sd=4.22) and females had an average of 69.1 dB SPL (sd=4.51). For minimal level of vocal effort, male participants had an average of 67.7 dB SPL (sd=3.42), while females had an average of 65.3 dB SPL (sd=4.68). Overall, male participants used higher level of SPL than female participants.

The correlation results were further analyzed by gender to determine if one gender was accounting for the significant relationships. For the comfortable vocal effort task, MFDR showed a high, significant correlation with SPL in male participants ($r = 0.878$, $p = 0.021$). A moderate but non-significant relationship between SPL and CPP sd in the comfortable vocal effort task was evidenced for males ($r = 0.528$, $p = 0.282$). In the maximal vocal effort task, moderate to high correlations were shown between SPL and MFDR ($r = 0.699$), translaryngeal airflow ($r = 0.655$) and CPP sd ($r = 0.735$), but these correlations were non-significant ($p \geq 0.096$). Female participants did not evidence any significant correlations between SPL and the aerodynamic or acoustic variables. Gender-specific correlational analysis must be interpreted cautiously due to the small number of male participants who were represented.

Discussion

In prior studies, aerodynamic and acoustic measures have distinguished certain voice disorders from healthy speakers, and have reflected physiologic differences in voice production for healthy speakers who have produced speech with varying voice quality dimensions such as pressed or breathy voice. The current study determined the changes in aerodynamic and acoustic features of voice that occurred when the level of vocal effort was varied in healthy speakers. Self-perceived ratings of vocal effort and external auditory-perceptual ratings of voice quality associated with the various levels of vocal effort were also assessed. Determining the aerodynamic and acoustic changes associated with increased or decreased vocal effort relative to comfortable effort may help identify the physiologic parameters that are critical to the high sense of vocal effort that many people with voice disorders experience. Identifying those parameters could then help clinicians target the critical variables in treatment when helping clients improve their voice while reducing their level of vocal effort.

Aerodynamics

Aerodynamic measures reflect the vibratory behavior of the vocal folds, and show changes from normative values when measured in people with hyperfunctional or hypofunctional voice disorders (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989; Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1990), or in people with healthy voice who produce differing voice qualities (Peterson et. al, 1994; Grillo & Verdolini, 2008)**.** Subglottal pressure reflects the driving forces directed from the trachea to the vocal folds at the onset of vocal fold vibration. Subglottal pressure is impacted by both respiratory and laryngeal factors, including the effects of increased lung volume initiation, expiratory respiration muscles and laryngeal adductor muscles. In the present study, participants significantly increased subglottal pressure between comfortable and maximal vocal effort tasks, and significantly decreased subglottal pressure when producing minimal vocal effort as compared to comfortable effort.

Researchers addressing the aerodynamic changes associated with varying voice qualities in healthy speakers alone (Peterson et. al, 1994; Grillo & Verdolini, 2008) have not reported specific findings on subglottal pressure. However, a comparison of our data to data of healthy speakers speech samples (presumably at comfortable levels of vocal effort) is important to verify that our participants showed typical aerodynamic patterns when producing speech at comfortable vocal effort. The average subglottal pressure for our participant group was 7.03cm H_2O during the comfortable vocal effort task, which is nearly identical to that found by Higgins, Netsell, & Schultz (1994) in their group of healthy adults with normal voice. These researchers found an average subglottal pressure of 7.01cm H_2O in their participant group during a sentence-reading task. The equivalent average subglottal pressure values of our participants when instructed to use a comfortable level of vocal effort during repeated syllable productions indicates that our participants showed phonatory behaviors that were representative of typical speakers.

Netsell, Lotz, & Shaughnessy (1984) compared aerodynamic and perceptual measures for 48 people with and without voice disorders, and found that higher subglottal pressures were associated with a rough and strained voice quality in people with voice disorders. Hillman and colleagues (Hillman, et al., 1989, 1990) found increased levels of subglottal pressure in people with voice disorders that were related to hyperfunctional patterns of voice production, including vocal nodules and vocal polyps. These authors suggested that increased laryngeal adductory muscle activity likely contributed to these elevated pressures during speech production. Although vocal effort was not assessed in those studies, voice disorders such as vocal nodules and polyps are often clinically associated with a reported increase in vocal effort. The elevated subglottal pressures evidenced by our healthy participants when producing maximal effort speech as compared to comfortable effort, along with the lower pressures associated with minimal effort speech suggest that subglottal pressure may be a key variable to address when treating patients with vocal hyperfunction who need to improve their voice and decrease their level of vocal effort during speech.

Translaryngeal airflow is impacted by both subglottal pressure and degree of laryngeal adduction. In this study, mean airflow that included the modulatory effects of the vocal tract was measured. Participants in the current study demonstrated airflow values that were consistent with typical levels produced during normal speech; during the comfortable vocal effort task, mean airflow values of 174.9 mL/sec were similar to normative values reported for females (177 mL/sec) during a sustained “ee” vowel (Colton, Casper & Leonard, 2006). Study participants significantly increased translaryngeal airflow when they produced speech with maximal *and* minimal vocal effort as compared to comfortable effort. In healthy adults mimicking breathy voice quality, Peterson, et al. (1994) found that airflow increased for breathy voice production relative to normal but decreased for pressed voice quality. Netsell, Lotz, & Shaughnessy (1984) found that combinations of lower airflows and higher subglottal pressures were associated with strained voice quality in their participants with voice disorders, whereas high pressures combined with high airflows were associated with the perceptual quality of roughness. When participants in the current study increased their level of vocal effort, *both* airflow and pressure increased significantly, and when they produced speech with minimal vocal effort, airflow significantly increased while subglottal pressure significantly decreased. A decrease or minimal change in subglottal pressure with an increase in translaryngeal airflow has been associated with a breathy voice quality in people with voice disorders (Netsell, Lotz, & Shaughnessy, 1984), and was also found in individuals with laryngeal pathology that reduces vocal fold closure during vibration (Hillman, et al., 1989, 1990). Our minimal vocal effort task was associated with breathy voice quality, and our findings of increased translarynegal airflow are consistent with the aforementioned studies that assessed airflow for speakers with a breathy voice quality. In contrast, during the maximal effort task our participants significantly increased airflow compared to comfortable effort, which differs from the reduction in airflow evidenced in prior studies when voice produced with strained or pressed quality was measured.

The participants may have used a more respiratory-based strategy for the maximal effort task, which would result in greater subglottal pressure with a concomitant increase in the amount of translaryngeal airflow. In contrast to the maximal vocal effort task, our participants may have used combined respiratory and laryngeal-based strategies for the minimal vocal effort task. By altering respiratory *and* laryngeal behavior simultaneously, subglottal pressure could be reduced while increasing translaryngeal airflow. However, because respiratory behavior was not measured in this study, which combinations of respiratory and laryngeal behaviors contributed to the changes in translaryngeal airflow cannot be definitively determined.

Unlike the other aerodynamic measures, laryngeal resistance did not significantly change when participants in the current study increased their vocal effort from comfortable level to maximum level. Trends in numeric values indicated lower laryngeal resistance for the comfortable versus maximal effort tasks. Very disparate standard deviations across the three tasks may have influenced the ability to find statistically significant differences for this comparison. In the current study, in contrast to the comparison of comfortable and maximal vocal effort, there was a significant difference between the comfortable and minimal vocal effort tasks. Grillo and Verdolini (2008) found that laryngeal resistance was the optimal aerodynamic variable for differentiating normal, breathy, and pressed vocal qualities in healthy adults. Although laryngeal resistance differentiated speech at comfortable and minimal vocal effort in the current study, its inability to differentiate speech at comfortable and maximal effort indicated that it was not an optimal differentiator of the physiologic patterns that contributed to maximal vocal effort. Several factors may account for the differences between our results and that of Grillo and Verdolini (2008). Participants in the current study targeted the physiologic component of increased vocal effort, rather than the auditory-perceptual target of strained voice quality in the Grillo and Verdolini study. Participants were purposely instructed in a manner that would avoid biasing them towards any specific physiologic target when varying their vocal effort. Thus, participants could have altered their vocal effort in numerous ways. Grillo and Verdolini (2008) demonstrated a pressed voice quality to their participants before having them produce their utterances, which may have given participants an auditory-perceptual target that was associated with increased laryngeal resistance (engaging more laryngeal adduction versus respiratory-based change). Furthermore, Grillo and Verdolini (2008) reported on measures of laryngeal resistance and vocal efficiency (a measure that includes SPL, translaryngeal pressure, and translaryngeal airflow). Without knowing the separate contributions of pressure and airflow, it is difficult to interpret the potential strategies that their participants may have used to produce the target voice qualities.

MFDR is derived from the inverse-filtered airflow signal, a process that removes the filtering effects of the vocal tract on the airflow waveform and produces an approximation of the unfiltered signal as it would be measured at the level of the vocal folds (Baken & Orlikoff, 2000). MFDR determines the rate of vocal fold deceleration that occurs during the closing phase of vocal fold vibration, thus reflecting the speed of vocal fold closure (Baken and Orlikoff, 2000; Peterson et al., 1994; Hillman et al., 1989). Higher MFDR values indicate faster speed and lower values indicate slower speed of vocal fold closure. Mean MFDR values demonstrated by our participants during the comfortable vocal effort task (319.9 LPS^2) were within the expected ranges as demonstrated by Perkell, Hillman, and Holmberg (1994) who found MFDR values that ranged from 164 to 337 LPS^2.

In the current study, the higher MFDR values that participants produced during the maximal vocal effort task and the lower MFDR values that were produced during the minimal vocal effort task indicate that a faster speed of vocal fold closure occurs with high vocal effort, whereas a slower speed of vocal fold closure is associated with minimal vocal effort. MFDR has been shown to increase in people with hyperfunctional voice disorders (Hillman, et al., 1989). Hillman and colleagues (1989) suggest that the increase in MFDR is associated with greater vocal fold amplitude and speed of tissue movement, which can lead to higher levels of collision forces and subsequent trauma to the vocal folds (Hillman, et al., 1989). The current study supports the relationship between vocal effort and increased MFDR, as there was a significant increase in MFDR between comfortable and maximal vocal effort tasks and a significant decrease in MFDR between minimal and comfortable effort tasks. Thus, the higher MFDR values produced by our healthy participants during the maximal vocal effort task may indicate that increased vocal effort puts people at greater risk for voice problems and vocal pathology due to the associated increase in collision forces during vocal fold vibration (Hillman, et al., 1989). The results of our study are also consistent with the Peterson et al. (1994) results showing similar trends in MFDR, with greater values occurring during pressed voice (which can be associated with greater vocal effort) and lower values during breathy voice (which can be associated with lower vocal effort).

Three of the four aerodynamic measures obtained during the current study showed significant differences for the comfortable to maximal vocal effort comparison and comfortable to minimal vocal effort comparison. Overall, these variables tended to increase with maximal vocal effort, and decrease with minimal vocal effort with the exception of translaryngeal airflow. These results may be useful for future studies addressing people with voice disorders. Understanding the patterns of typical speakers who volitionally alter their level of vocal effort can help predict possible patterns that people with voice disorders may exhibit, and how those physiologic patterns may influence their voice disorder and potential for improvement in therapy. Future studies that include people with specific voice disorder etiologies will be needed for comparison to the current findings in normal speakers.

The greatest effect sizes were seen when comparing the translaryngeal airflow and subglottal pressure of comfortable versus maximal vocal effort. A strong effect size was also seen when comparing the subglottal pressure of comfortable versus minimal vocal effort and when comparing the MFDR of comfortable versus maximal vocal effort. These strong task differences suggest that subglottal pressure, translaryngeal airflow, and MFDR have a pivotal role in voice that is produced with altered vocal effort. Thus, respiratory or laryngeal forces associated with increased driving pressure at the onset of vocal fold vibration (which relate to subglottal pressure and airflow), and higher speeds of vocal fold closure may be important factors that contribute to an increased sense of vocal effort.

Acoustics

In the current study, CPP and its standard deviation were examined for each of the speaking tasks to determine how these acoustic variables were affected by the altered physiology and aerodynamics associated with change in vocal effort. These acoustic measures are of interest because they significantly differentiate various voice disorders from normal speakers (Awan & Roy, 2005; Eadie & Doyle, 2005), and show strong capacity to predict perceptual dysphonia severity (Lowell, Colton, Kelley, & Hahn, 2011; Awan & Roy 2005, 2009; Awan, Roy, & Dromey, 2009). In normal speakers, higher CPP values can occur for speech produced at greater SPL and for speech produced by males versus females (Awan, Giovinco, & Owens, 2012). Although most studies have determined mean CPP or CPP sd values for normal speakers during a different vowel than the "ee" used in our study, Awan, Giovinco and Owens (2012) reported a mean value for CPP smoothed (analogous to our measure of CPP but computed through different software) of 6.5 dB, which is highly similar to the CPP mean of 6.7 dB that participants showed in our comfortable vocal effort task.

In the current study, CPP was significantly higher when participants produced speech with maximal vocal effort as compared to comfortable vocal effort. In people with voice disorders, several previous studies have found that a strained voice quality will lead to a significantly *lower* CPP than that of normal participants (Lowell, et al., 2012; Awan, Roy, Jette, Meltzner, & Hillman, 2010; Awan & Roy, 2005; Eadie & Doyle, 2005). In voice disorders, aperiodicity of vocal fold vibration and additive noise in the signal are common, and lower the relative harmonic energy in the signal, thus producing lower CPP values for those participants. These acoustic elements may not be easily mimicked by normal speakers when producing speech with a maximal level of vocal effort. This likely contributed to the differing CPP results of participants in the current study as compared to studies addressing people with voice disorders, even though the common element of increased vocal effort was present in both.

The standard deviation of the CPP (CPP sd) reflects the degree of variability of CPP values across the entire speaking sample being analyzed. When participants in the current study produced speech with minimal vocal effort, CPP sd was significantly lower than during the comfortable vocal effort task. During continuous speech, CPP sd is significantly lower for people with voice disorders as compared to normal speakers (Lowell, et al., 2012; Lowell, et al., 2011; Awan, et al., 2010). This lower CPP sd during continuous speech for people with voice disorders may reflect less flexibility in voicing, with reduced fundamental frequency and SPL variation (Awan, Giovinco, & Owens, 2012; Lowell, et al., 2011)**.** For the normal speakers in the current study, reduced variation in phonatory patterns may have been part of how they minimized their vocal effort, yielding lower CPP variation.

Male and female participants used differing levels of SPL during this study. Male participants produced each speaking task at levels of approximately 3 to 7 dB higher than that of females for each task. Correlations of all aerodynamic and acoustic variables with SPL were computed to determine the degree to which SPL versus other phonatory behaviors may have contributed to the significant task differences evidenced in this study. Although some significant relationships were found, correlation coefficients for most dependent variables were ~0.55 or less, explaining approximately 30% of the variance. Furthermore, the gender-specific correlation analyses showed that all relationships between SPL and the dependent variables were associated with the male, not female participants, with females representing the majority of our participants. Taken together, these analyses indicate that the aerodynamic and acoustic differences evidenced between tasks were not primarily associated with SPL differences, but rather other phonatory behavior differences. Our results are consistent with an early study by Brandt, Ruder and Shipp (1969), which indicated that listeners have distinct perceptual representations for loudness and vocal effort that include the acoustic cues of SPL and stimulus bandwidth. Thus, while vocal effort and SPL can positively co-vary, production and perception of vocal effort do not appear to be based on SPL alone.

Perceptual ratings in this study provided additional verification of the validity of the speaking tasks and indicated that voice quality is affected by alterations in vocal effort. Self-perceived levels of vocal effort were assessed by having participants rate their vocal effort after every production. Means of these ratings indicated that the tasks were performed in the manner that was targeted; maximal and minimal vocal effort tasks were rated with numerically different effort levels than the comfortable vocal effort task. External ratings of voice quality showed numerically higher mean values for strain during the maximal effort task and numerically higher values for breathiness during the minimal vocal effort task. These results are consistent with studies that have included voice-disordered participants with either hyperfunctional or hypofunctional voice disorders (Lowell et al., 2012). The perceptual dimensions of breathiness and strain showed opposite relationships in our participants, which is expected as breathiness and strain are considered to be opposite on a continuum of voice quality. Strained voice quality is often associated with hyperfunctional voice disorders (Kempster, Gerratt, Verdolini, Abbott, Barkmeier-Kraemer, & Hillman, 2009; Boone, McFarlane, Von Berg, & Zraick, 2010), whereas breathiness is associated with hypofunctional conditions such as unilateral vocal fold paralysis (Watts & Awan, 2011).

Study Limitations and Future Directions

There were several limitations to this study that future research could potentially improve upon. This study included healthy participants with normal voice. Our interest in determining the physiologic contributions to vocal effort is based on the common feature of increased vocal effort in people with voice disorders. Therefore, the ultimate interest in assessing the physiology of vocal effort is how that can be applied to people with voice disorders. We required our participants to volitionally vary their level of vocal effort across speaking tasks, which is often not possible for people with voice disorders who often present with consistently elevated vocal effort. Therefore, as a preliminary study, we focused on people with normal voice. Future studies should compare the physiologic features of voice in people with and without voice disorders. Additionally, the number, age range, and gender distribution of our participants were restricted, which limits the ability to generalize these findings. It would be advantageous to include multiple age ranges and greater participant numbers in future studies.

The tasks and instructions that were included in our study procedures also had limitations. The definition of vocal effort was purposely broad so as not to restrict participants in their physiologic manifestation of vocal effort. Some researchers have provided auditory examples to participants when having them target particular voice qualities (Grillo & Verdolini, 2008). The advantage of providing a model is that participants will be more consistent in how they perform the task. However, the disadvantage to modeling is that the researcher then influences the outcome of the task, which we wanted to avoid. Finally, the repeated /pi/ syllable task that our participants performed was implemented because it allows the appropriate phonetic and valving conditions needed for our aerodynamic measures. However, this is also a contrived speaking task that is less representative of typical conversational speech. Future studies might include sentences loaded with /pi/ consonant-vowel combinations to elicit the necessary phonetic context in a more naturalistic speaking task.

Conclusions

The current study found many significant differences in aerodynamic and acoustic measures when healthy speakers varied their level of vocal effort across speaking tasks. For the majority of measures, maximal vocal effort was associated with an increase in aerodynamic and acoustic dimensions of voice. Subglottal pressure, translaryngeal airflow and MFDR showed the strongest effects when determining differences between maximal and comfortable vocal effort. These findings, although preliminary, may help identify the physiologic parameters that are primarily associated with a sense of increased vocal effort, which is commonly experienced by people with neurological, organic and functional voice disorders. By determining the primary aerodynamic features that are associated with increased vocal effort, clinicians can then target these variables in voice therapy to improve voice while reducing sense of vocal effort. Participants' self-perceived changes in vocal effort showed that perceived variations in sense of effort matched the goal for each task (to produce maximal or minimal vocal effort), helping to validate these experimental tasks. Future studies should focus on comparing the present study with a population of people with voice disorders commonly associated with strained voice quality and increased vocal effort.

Appendix A: Participant Instructions and Experimenter Procedures

After consent process, start with hearing screening and voice screening in the sound booth

TAKE SHORT REST, GIVE SUBJECT SOME WATER

Training, Pitch

We are going to start by practicing the tasks that we will be doing later today

First I would like you to repeat the syllable /pi/ seven times while you are at a target pitch level. Let's record an example at the correct pitch level.

a. Attach microphone to subject
b. Open RealPitch from desktop icon, practice target level and record a /pi/ production at that level
c. Prompt participant to either raise or lower pitch as needed

Training, Pace

Next, we are going to show you the pace that you need to be at when you produce these syllables.

I will play this metronome and you can begin by tapping while you say the syllables. I'd like you to say /pi/ seven times with the metronome.

Now try that same task again without tapping your hand.

Now try the same thing without the metronome.

Now we'll do that one more time and I'll record it as a model of your correct pitch and pace

Training, Effort

That was at a level of what I would call a ***comfortable vocal effort***. Many systems contribute to vocal effort, including the breathing and voice systems. I'd like you to assign a number to the amount of vocal effort that you used for that task. You can use a scale of 0 to 10, or any scale you want. What number would you use to describe that level of vocal effort?

Now you will repeat the /pi/ syllable at the target pitch and rate, but with a ***minimal level of vocal effort***. This should be an easy, relaxed voice, like when answering a question about whether you like ice cream with "mmmhmmm". If your comfortable production was a _______, your minimal vocal effort should be less than that. Produce it in a way that feels least effortful for you.

a. Bring pitch headband mic closer to subject's mouth

Go ahead when you are ready

What number would you use to describe that level of vocal effort?

Great, now repeat /pi/ seven times with your ***minimal vocal effort*** level, and try to stay at the same pitch as you were before, and the same rate. Here's an example of your pitch and rate for the comfortable vocal effort task.

a. Play model recording

b. Cue subject to modify pitch or rate if needed

Great, now I'd like you to repeat the /pi/ syllable at a ***comfortable vocal effort***, at the target pitch and rate. Here's the model to remind you:

a. Play model recording

b. Have subject produce one syllable sequence at comfortable vocal effort

Now I'd like you to produce those syllables with your ***maximum vocal effort***. This should be an effortful, forceful voice, like when scolding or correcting a pet that has done something wrong. If your comfortable production was a _______, your maximal vocal effort should be more than that. Produce it in a way that feels <u>most</u> effortful for you.

What number would you use to describe that level of vocal effort?

When you're ready, say /pi/ seven times at your maximal vocal effort, at the target pitch and rate. You can check your pitch on the computer screen.

TAKE SHORT REST, GIVE SUBJECT SOME WATER, START PREPARING PNEUMOTACHOMETER EQUIPMENT

Recordings

Now we are ready to do the recordings. I will be putting a mask on you that covers the nose and mouth, but it has mesh openings so you will be able to breathe freely. A small tube is attached to the mask that will go between your lips. You will be doing all of the same tasks we just practiced while we record the airflow coming from your mouth.

a. Place mask on subject, check for good seal at bridge of nose and chin

b. Have subject hold the mask on their face to assure good seal

Now that the mask is in place, we are going to do those repeated /pi/ syllables at the target pitch and rate. We'll start at your ***comfortable level of vocal effort***. Here's the model to remind you:

a. Play model recording

Go ahead and practice that once with the mask in place

a. Cue subject to modify pitch or rate if needed

That was great, now we'll record some sets. I'll say "go" when we are ready.

(After first recording) What number would you use to describe that level of vocal effort?

a. Record two more sets of seven /pi/ syllables at comfortable vocal effort

b. Verify that pressure peaks for at least some syllables in each set are similar

c. Verify that pressure returns to near zero for every syllable

Now we'll record some at your ***minimal vocal effort***. You will do these at the target pitch and rate, but now at your minimal vocal effort. If your comfortable production was a _______, this should be less than that. [bring pitch head mic closer to subject's mouth].

I'll say "go" when we are ready.

What number would you use to describe that level of vocal effort?

a. Record two more sets of seven /pi/ syllables at minimal vocal effort

Now we'll record some at your ***maximal vocal effort***. You will do these at the target pitch and rate, but now at your maximal vocal effort. If your last production was a _______, this should be more than that. I'll say "go" when we are ready.

What number would you use to describe that level of vocal effort?

a. Record two more sets of seven /pi/ syllables at maximal vocal effort

Appendix B: Tables and Graphs

Table 1												
Descriptive Statistics for Aerodynamic Measures												
Condition	**Subglottal Pressure (cm H_20)**		**Translaryngeal Airflow (mL/sec)**		**Translaryngeal Resistance (cm H_20/mL/sec)**		**MFDR (LPS^2)**		**Vocal Effort**		**Sound Pressure Level (dB SPL)**	
	Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation	Mean	Std Deviation
Comfortable	7.03	2.33	174.87	68.06	0.07	0.09	319.91	194.30	4.04	1.44	67.55	4.34
Maximum	10.19	4.55	236.55	60.00	0.04	0.01	540.96	331.79	7.46	1.44	71.40	5.54
Minimum	5.37	1.10	202.72	79.78	0.03	0.01	229.61	115.18	1.87	0.83	66.11	4.50

Table 2				
Descriptive Statistics for Acoustic Measures				
Condition	**CPP (dB)**		**CPP SD (dB)**	
	Mean	Std Deviation	Mean	Std Deviation
Comfortable	6.66	2.53	2.55	0.98
Maximum	7.90	2.18	2.62	0.66
Minimum	5.84	2.61	2.11	0.71

Table 3			
	***t*-score (for *t*-tests only)**	**Significance**	**Effect Size (Cohen's *d*)**
Pressure			
Comfortable vs. Maximal		<0.001	-0.874
Comfortable vs. Minimal		0.011	0.914
Translaryngeal Airflow			
Comfortable vs. Maximal	14.857	0.001	-0.962
Comfortable vs. Minimal	4.946	0.040	-0.376
MFDR			
Comfortable vs. Maximal		<.001	-0.813
Comfortable vs. Minimal		0.002	0.565
Translaryngeal Resistance			
Comfortable vs. Maximal		0.711	0.469
Comfortable vs. Minimal		0.002	0.625

Table 4				
	***t*-score**	**Significance**	**Observed Power**	**Effect Size**
CPP				
Comfortable vs. Maximal	17.387	0.001	0.975	-0.524
Comfortable vs. Minimal	3.937	0.064	0.465	0.319
CPP sd				
Comfortable vs. Maximal	0.175	0.681	0.068	-0.084
Comfortable vs. Minimal	11.966	0.003	0.903	0.508

Figure 1: Instrumentation

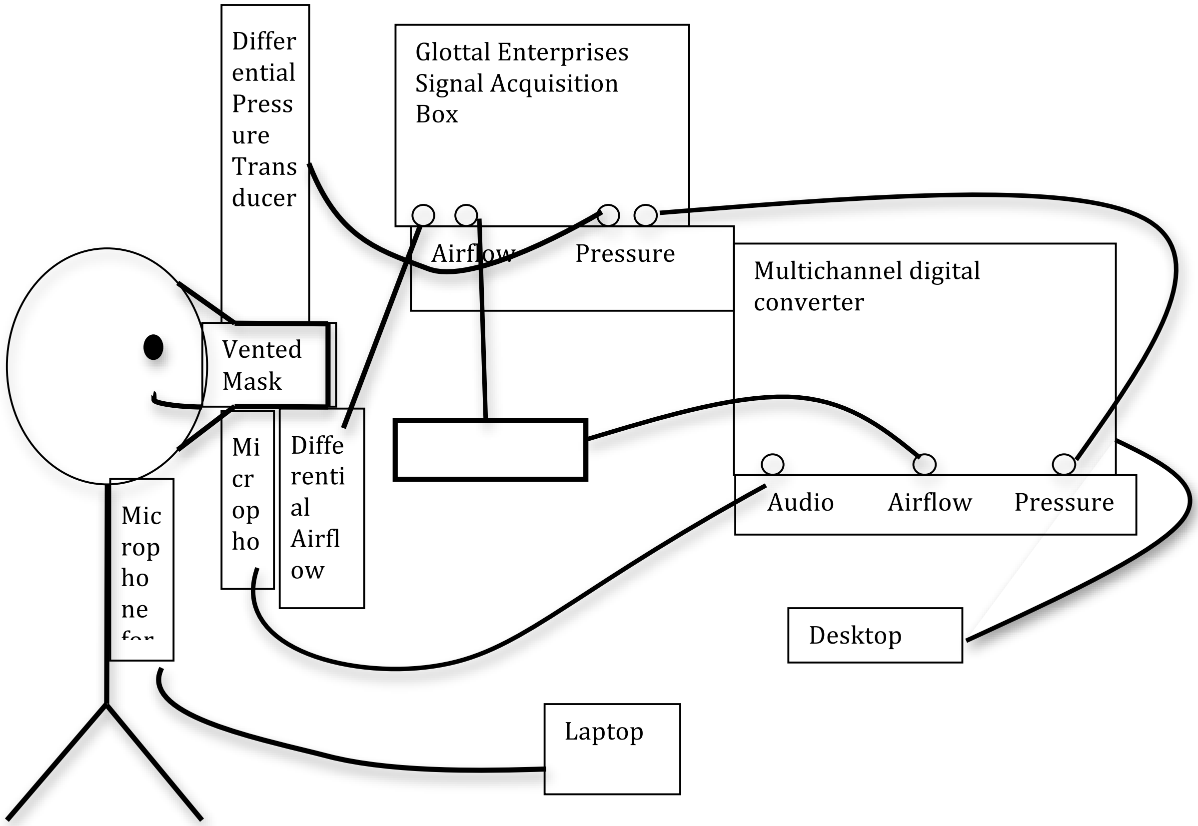


Figure 2: Mean subglottal pressures (cm H_20) for each speaking task

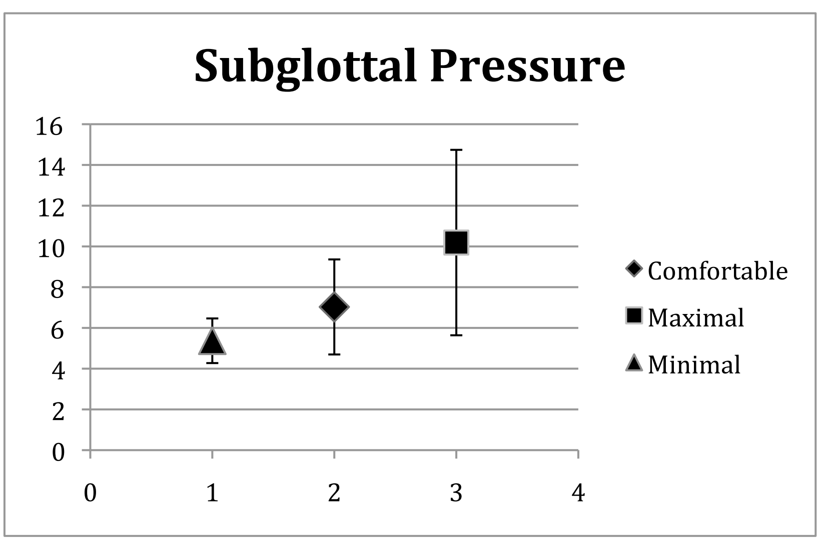


Figure 3: Mean translaryngeal airflow (mL/sec) for each speaking task

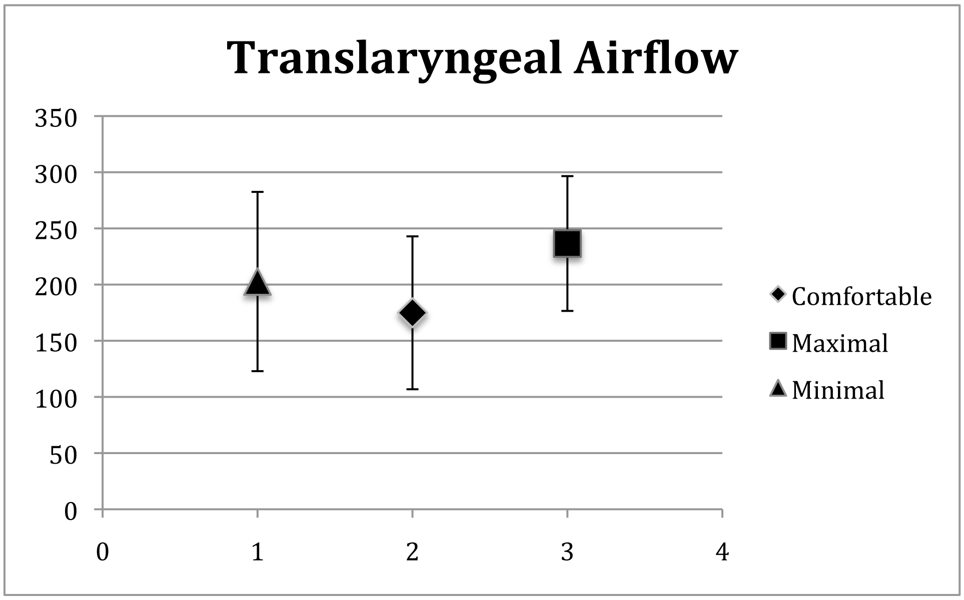


Figure 4: Mean laryngeal resistance (cm H_20/mL/sec) for each speaking task

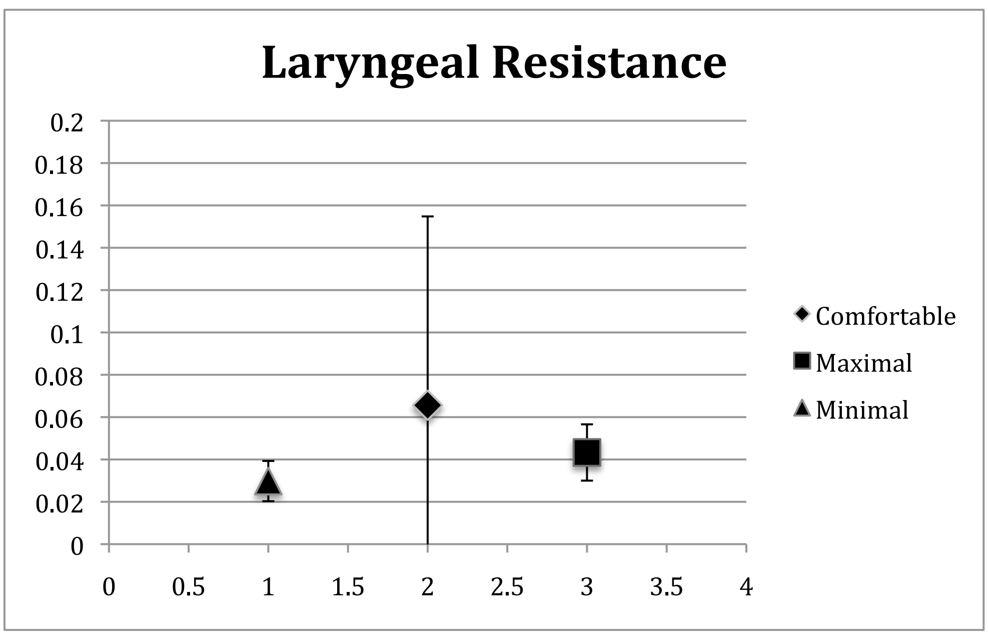


Figure 5: Mean maximum flow declination rate (MFDR, LPS^2) for each speaking task

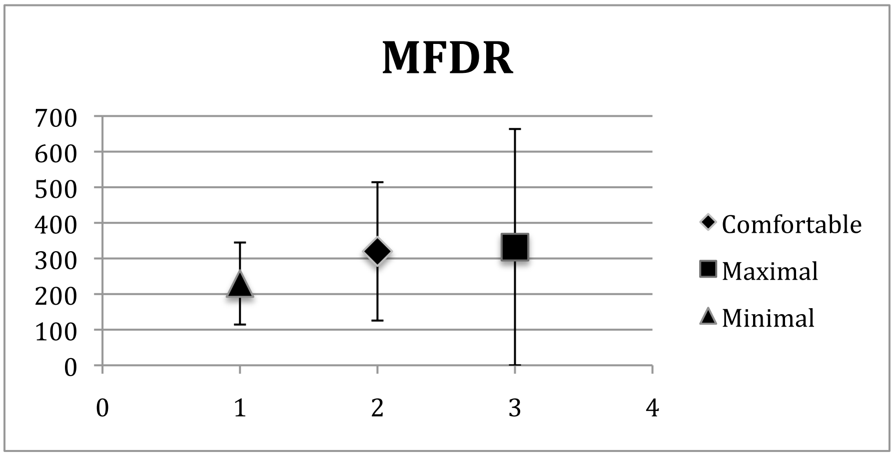


Figure 6: Mean cepstral peak prominence (CPP, dB) for each speaking task

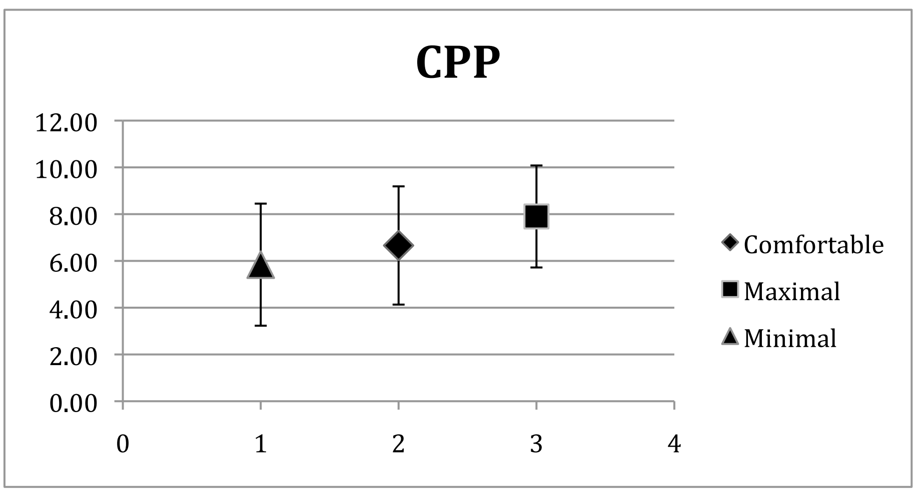
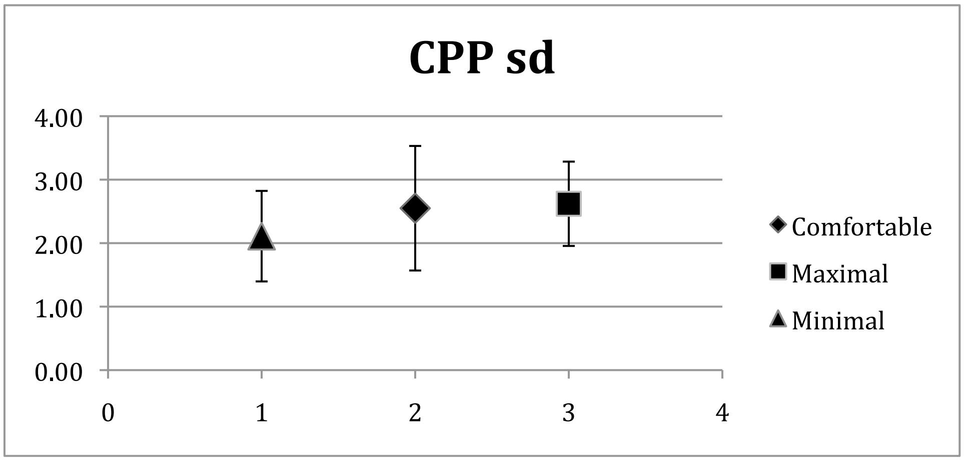


Figure 7: Mean cepstral peak prominence standard deviation (CPP sd, dB) for each speaking task



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