CONTRIBUTIONS OF THE LARYNX TO VOCAL TREMOR PERCEPTION

By

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ABSTRACT

Vocal tremor is caused by an abnormal rhythmic modulation of pitch and loudness affecting the voice. This is caused by tremor present in the musculature and structures within the speech mechanism which is composed of the respiratory, laryngeal, and vocal tract. The degree and manner to which each of these components of the speech mechanism contribute to the perception of vocal tremor is unknown. The purpose of this study was to determine the perceptual threshold of vocal tremor caused by either fundamental frequency modulation, or glottal width modulation, affecting loudness stability. Computer-generated voice samples were used to study the magnitude of each type of modulation necessary for naïve listeners to accurately identify the presence of vocal tremor. Modulation of glottal width had an average threshold of 4%. This was lower and more stable across listeners than the average threshold for perception of fundamental frequency modulation at 8% magnitude. These findings demonstrate that listeners were more sensitive to the presence of laryngeal modulation affecting glottal width than modulation of fundamental frequency. Acoustic analysis of the modulated stimuli may identify unique features to each type of modulation that could explain the differences in threshold and consistency observed.

INTRODUCTION

Vocal tremor is a perceptual phenomenon characterized by a rhythmic fluctuation in pitch and loudness. The acoustic output heard as vocal tremor results from spontaneous oscillatory movement of musculature within the speech mechanism to magnitudes that result in visibly affected articulator movement in affected structures (Gottlieb & Lippold, 1982). Periodic oscillations in the speech mechanism can be measured as modulation of frequency and intensity.

The easiest speech context for perceiving vocal tremor is during sustained voicing such as during production of vowels. However, as vocal tremor severity increases, it may also be detected in connected speech. Severely affected individuals tend to slow their rate of speech and prolong voiced speech sounds during speaking. This compensatory speaking pattern results in enhanced perception of vocal tremor (Tomoda, Shibaski, Kuroda, & Shin, 1986). Tremor tends to be more difficult to detect in connected speech because the average rate of vocal tremor is typically slower than the average rate of speech production (3-4 syllables per second). That is, transitions from voiced to voiceless sounds during connected speech may disrupt the periodic or rhythmic variation in fundamental frequency and intensity typically heard during sustained voicing resulting in less prominent perception of vocal tremor. As the severity of the vocal tremor worsens, individuals often slow their rate of speech and prolong voiced speech sounds. This results in more audible vocal tremor during connected speech (Ludlow, 1995).

Vocal tremor and tremor present in other parts of the body result from a neurological pathology. The regions of the brain associated with tremor vary with diagnosis. For example, individuals with Parkinson disease exhibit a resting tremor. The ‘pill-rolling’ movement of the thumb and fingers is an example of how this resting tremor may manifest in such individuals (Matsumoto, 2000). Resting tremor is typically associated with impaired function of the basal ganglia loop that results in synchronization of neurons that were once independent (Deuschl, Raethjen, Lindemann, & Krack, 2001). Essential tremor is associated with impaired function of the olivocerebellar circuit (Deuschl, 2001). Damage to this circuit can result in both intention and postural tremor. Intention tremor is characterized by a sudden exaggerated movement in the terminal portion of an action. In contrast, postural tremor is elicited when the muscle of an affected body part is contracted. This type of tremor can be seen in patients as a back-and-forth or side-to-side oscillation of the head. It is also evident in limb movement (Matsumoto, 2000). There are several types of neurologic etiologies that can result in vocal tremor. However, Essential Tremor is probably the most common diagnosis in individuals presenting with a vocal tremor.

Clinical therapy to treat vocal tremor often does not focus on one portion of the speech mechanism in specific, but the whole mechanism. Likewise, often the first professional of contact for a person who believes they may be experiencing some type of vocal disorder is a primary care physician or neurologist. This person may not necessarily be an expert in voice and tremor disorders and would most likely use a non-standard perceptual method for determining vocal abnormality. As a result, judgments about vocal tremor and severity could vary from one physician to another. By the time a physician refers a patient to a voice expert, the vocal tremor is typically perceptible to naïve listeners. Speech-Language Pathologists and Otolaryngologists with expertise in voice are the typical professionals to judge the presence of a vocal tremor and its severity. Otolaryngologists usually visualize the abnormal movements of the pharynx, larynx, base of tongue, or soft palate (Bové, Daamen, Rosen, Wang, Sulica, Gartner-Schmidt, 2006). Although SLPs may also visualize the same structures and evaluate the degree to which they appear affected by a tremor, they also utilize structured acoustic and perceptual measurements to evaluate the presence and nature of the voice disorder. Several free software programs are available with which to measure acoustical parameters such as fundamental frequency, intensity, and spectrographic information. These parameters allow clinicians to visualize rhythmic low frequency modulation in the voice signal associated with the vocal tremor.

One vocal tremor assessment system was recently developed by Bové et al. (2006) to standardize the visual-perceptual evaluation of vocal tremor as a consequence of tremor visually affecting the structures of the oropharynx and larynx. Using nasoendoscopy, this scale rates severity of observed tremor affecting the palate, base of tongue, pharyngeal walls, larynx, supraglottis, and true vocal folds. It does not include ratings for the jaw, head, or respiratory system which could also be contributing to the perception of vocal tremor. Further, it does not distinguish the specific manner of tremor observed affecting the larynx such as adductory modulation versus elongation/shortening patterns that would affect fundamental frequency.

Vocal tremor is associated with the presence of tremor in one or more components of the speech mechanism. Although not previously studied, it is hypothesized that tremor affecting each subsystem within the speech mechanism would contribute differently to the acoustics of vocal tremor. For example, tremor affecting the respiratory system would be expected to contribute to modulation of lung pressure during speech resulting in associated changes in vocal intensity. Given the slower rate at which the larger respiratory structures can be modulated, vocal tremor associated with the respiratory system would most likely be measured at 3-5 Hz and primarily affect vocal intensity. In contrast, tremor affecting the larynx could modulate vocal fold vibration rate and glottal width. Changes in vocal fold vibration rate would occur through modulation of the muscles that shorten (thyroarytenoid) or stretch (cricothyroid) the vocal folds. Previous research by Finnegan and colleagues (1999) showed that these laryngeal muscles typically exhibit a rate of modulation between 5-7 Hz during phonation. The impact of laryngeal muscle tremor affecting vocal fold length changes would result in fundamental frequency modulation which, in turn, would affect intensity modulation. That is, the latter results from an unaffected vocal tract configuration through which the F_o and its harmonics would shift upward and downward resulting in changing amplification of the harmonics by way of formant peaks in the “filter system.” In addition to tremor affecting vocal fold vibration, laryngeal musculature associated with adduction (lateral cricoarytenoid and interarytenoid) and abduction (posterior cricoarytenoid) of the vocal folds could occur. The result of such modulation would primarily affect the glottal width during phonation. This would result in modulation of intensity during phonation. Finally, extrinsic laryngeal musculature might exhibit the presence of tremor indicated by vertical changes in laryngeal position within the neck. Modulation of laryngeal height would alter vocal fold stiffness and glottal width associated with passive stretching of the conus elasticus and resulting abduction of the vocal folds. Thus, both Fo and intensity would be modulated at the level of the larynx in this case.

Finally, tremor affecting the articulators comprising the vocal tract may, or may not impart the perception of vocal tremor. For example, pharyngeal modulation compared to jaw and tongue modulation would be expected to affect the acoustic output to differing degrees. The primary impact of modulation of vocal tract components would be expected to change the formants of the vocal tract. Thus, modulations within the vocal tract may not affect fundamental frequency, but may result in perceived intensity modulations associated with shifts in the peak energy of the harmonics associated with formants 1 and 2. The rate of this modulation would depend upon the size of the affected structure, but would likely result in a rate somewhere between 5-8 Hz. Further, the degree to which vocal tremor would be evident in this context would be most related to the shape of the vocal tract and the F_o of the speaker.

Little is currently known about the specific contributions of each component of the speech mechanism to the perception of tremor. The purpose of this study is to investigate the contribution of tremor affecting vocal fold adduction and abduction (glottal width modulation) and vocal fold vibration (length change modulation) to the perception of vocal tremor in naïve listeners. Given the direct involvement of the larynx in converting the airstream from the lungs into sound for speech production, it is hypothesized that modulation of fundamental frequency and intensity at the level of the larynx will be detected at low magnitudes (less than 10% modulation).

METHODS

This study was approved by the Institutional Review Board at the University of Arizona. Thirty participants (4 males, 26 females) served as listeners for this study. Volunteers were recruited using flyers and electronic postings within the Department of Speech, Language, and Hearing Sciences. Participants were required to be over the age of 18 years and reported having normal hearing and little or no familiarity with vocal tremor. The ages of participants ranged from 18-40, the average age being 21. Before initiation of the experiment, participants underwent a hearing screening with pure tones at 25 dB HL at 500, 100, 200, and 4000 Hz. They were required to hear all tones in order to pass and continue with the study.

Vocal Tremor Stimuli:

Computer generated voice samples served as the stimuli for this study. These were generated with a kinematic model of the vocal folds (Titze, 2006) that was acoustically and aerodynamically-coupled to a wave-reflection model of the trachea and vocal tract (Liljencrants, 1985; Story, 1995). The wave propagation algorithm included energy losses due to yielding walls, viscosity, heat conduction, and radiation at the lips. The trachea extended from the glottis to the bronchial termination and was idealized as a tube tapered from 0.3 cm^2 just below the glottis to a constant area of 1.5 cm^2. The system was driven by the respiratory pressure (P_R) assumed to exist at the bronchial end of the trachea. In generating each sample for this study, P_R

was ramped from 1000 to 7840 dyn/cm^2 in 10 ms with a cosine function, and then ramped down from to 7840 to 1000 dyn/cm^2 over the final 100 ms of the utterance; this circumvented production of transient artifacts that may distract a listener during presentation of the audio samples. Control parameters for the vocal fold model consisted of fundamental frequency, length and thickness of the vocal folds, degree of posterior adduction, medial bulging of the vocal fold surface, the nodal point around which the surface vibrates, and respiratory pressure. The shape of the vocal tract was controlled with a model of the vocal tract area function (Story, 2005). For this study two of the control parameters related to laryngeal function were chosen to be modulated: fundamental frequency and vocal fold adduction/abduction (i.e., glottal width modulation).The amount of modulation ranged from 0%-15% in both parameters and simulated changes which could account for the perception of vocal tremor. A 110 Hz fundamental frequency was used to simulate a male voice during sustained voicing of the vowel, "ah." Each stimulus was generated with a 5 Hz tremor of only one of the parameters and each had a duration of 1 second. Each participant only listened to signals of one modulated parameter.

Training stimuli consisted of 5 signals of with no audible tremor and five signals with audible tremor all presented in random order. The level of audible tremor was produced by changing the percent modulation extent in either parameter. A higher modulation corresponds to a more audible tremor. Stimuli in the adduction experiment consisted of samples at 8.5%, 9.5%, 10.5%, 12%, and 14% modulation extent. These five stimuli were presented in random order along with five stimuli at 0% modulation. Stimuli for the frequency experiment consisted of samples at 10%, 13%, 15%, 25%, and 35% modulation extent. These five stimuli were also presented in random order along with five stimuli at 0% modulation. Both training sessions were independent session with a different set of participants.

Experimental stimuli exhibited a range of F_o and adductory modulation that varied from 0% modulation by intervals of .3% modulation and at intervals of .5% from 2-10% modulation. A series of stimuli were generated exhibiting progression of increasing modulation associated with F_o changes and then another series was generated to exhibit progressive changes in adductory modulation. Thus, two different sets of stimuli were developed for this study- one set each for two different groups of listeners.

To test perceptual ratings of laryngeal modulation of vocal fold adduction, 22 stimuli pairs were presented four times in random order. To test perceptual ratings of laryngeal modulation of fundamental frequency, 24 stimuli pairs presented four times in random order. In both cases, the stimuli ranged from 0% modulation extent up to approximately 14% modulation extent separated by .5% intervals of modulation.

Each experimental stimulus trial presented listeners with two stimuli- one at a percentage of modulation of the particular parameter (F_o vs. adduction modulation) and the second at 0% modulation. All stimuli were repeated 4 times and participants were asked to discriminate between the two as ‘same’ or ‘different’.

Vocal Tremor Training Session:

The listening tasks were performed in a sound booth with listeners seated 2 to 3 ft directly in front of a loudspeaker (Tannoy). Computer-generated voice stimuli were presented through the speaker at a comfortable loudness level to individual listeners. The training listening session preceded the experimental listening task.

Listeners were presented with the computer generated training samples through a psychological testing program (Alvin) one at a time and asked to identify the presence or absence of tremor by selecting “Yes” (the vocal tremor was audible) or “No” (the vocal tremor was not audible). Participants were given the option of replaying the sample at their discretion. A total of ten stimuli were presented twice. In order to pass training, the participant was required to answer correctly 80% of the time. Each participant was given 3 attempts to pass the training activity. If they passed the training activity, they were permitted to continue with the experimental listening task. After a successful completion of training, participants were asked to provide the experimenter with a verbal description of signals identified as vocal tremor. This was done in order to collect terminology for describing vocal tremor that is familiar to naïve listeners that can be used in future studies of vocal tremor.

Experimental Procedures:

The experimental task involved discrimination of two computer generated voice samples, one without modulation and one either without or with varying degrees of vocal tremor modulation. The participants selected the ‘start’ button after which the two voice samples immediately played. Participants were asked to rate whether the two voice samples were the ‘same’ or ‘different’ using the Alvin software program. Participants were able to ‘replay’ the sound at their discretion and allowed one 15 minute break, if needed.

Participants were alternatively inducted into one of two studies: vocal tremor associated with laryngeal modulation of F_o or laryngeal modulation of vocal fold adduction (glottal width modulation). Participants rated experimental stimuli of one or the other type, but did not complete ratings on both sets of stimuli.

Each signal pair was shuffled twice so that each percentage of modulation was heard four times in total. This created a total of 88 trials for the adduction experiment and 96 trials for the fundamental frequency experiment. All experimental stimuli pairs were presented to each listener in random order following an AB and BA paradigm. That is, the order of each pair of experimental stimuli was random; however, each experimental stimulus pair was presented twice using the AB order and twice using the BA order.

Data Collection and Analysis:

Upon completion of ratings of experimental stimuli pairs, listener responses were exported to Matlab for analysis. A Matlab command file extracted the response of listeners for each experimental stimulus pair and plotted individual plot of accuracy in responding that pairs were the same or different (0-100%) across the four trials for each modulation stimulus (0 – 15%). Once data collection was completed, the same plot was generated as an average across all listeners to determine the average degree of modulation present before listeners demonstrated 100% accuracy in identifying that the 0% and modulated stimuli were different. The level of modulation at which, on average, listeners accurately identified the presence of vocal tremor for each of the tested parameters (F_o v adduction) was determined from this plot. Comparison of the same individual plots was also completed to determine variability across individuals, or the range in the threshold of perception of vocal tremor.

Data Analysis:

The average threshold at which naïve listeners detected the presence of a vocal tremor was determined for modulation of adduction (glottal width) during voicing and of fundamental frequency. A total of 4 trials of each level of modulation were randomly presented to listeners paired with a normal (non-modulated) voice and rated as the same or different than 0% modulation. Threshold of vocal tremor detection was defined as the point at which 75% or more of the trials were accurately identified to have a vocal tremor for three sequential modulation levels and after which accuracy did not drop below 75% accuracy on subsequent modulation levels.

RESULTS

Modulation of vocal fold adduction: On average, the threshold for detection of vocal tremor due to adductory modulation of the vocal folds during voicing was determined to be at 4% ranging from 3-6.5% (See Figure 1A). That is, the modulation of vocal fold adduction occurred at 4% of the glottal width of 2 mm to which the vocal folds adducted for phonation. Although this particular modulation of the larynx showed fairly consistent detection of vocal tremor once threshold was reached across almost all listeners (See example in Figure 2B), one participant did exhibit inconsistency after reaching the criterion for threshold (See Figure 2A). Out of 15 participants, 13 exhibited a threshold beyond which they did not drop below 75% accuracy in identifying the presence of vocal tremor and 2 exhibited inconsistency such as displayed in Figure 2A. Thus, only a small proportion of listeners exhibited inconsistency (Figure 2B); however, the overall pattern of accuracy in identifying vocal tremor supports accurate identification at 4% modulation.

Modulation of fundamental frequency: On average, modulation of fundamental frequency had an average threshold of 8% with a range from 5.5-14% (see Figure 1B) in those achieving the criteria for reaching threshold. Modulation of this parameter was associated with a wide range of performance, including that 5 out of 15 individuals did not achieve a threshold of accuracy, similar to the example shown in Figure 3B. Figure 3A shows a participant who reached threshold and stayed above threshold.

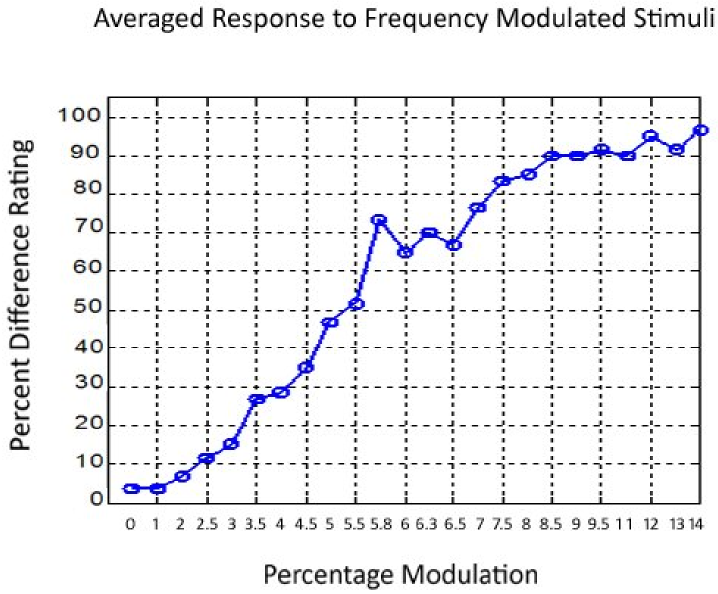

Figure 1A: Average percentage response of 'different' across all subjects in frequency-modulated stimuli.

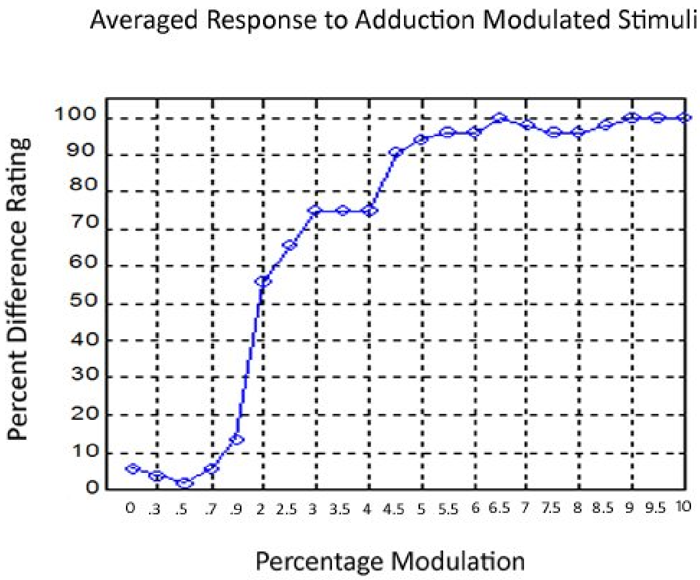

Figure 1B: Average percentage response of 'different' across all subjects in adduction-modulated stimuli.

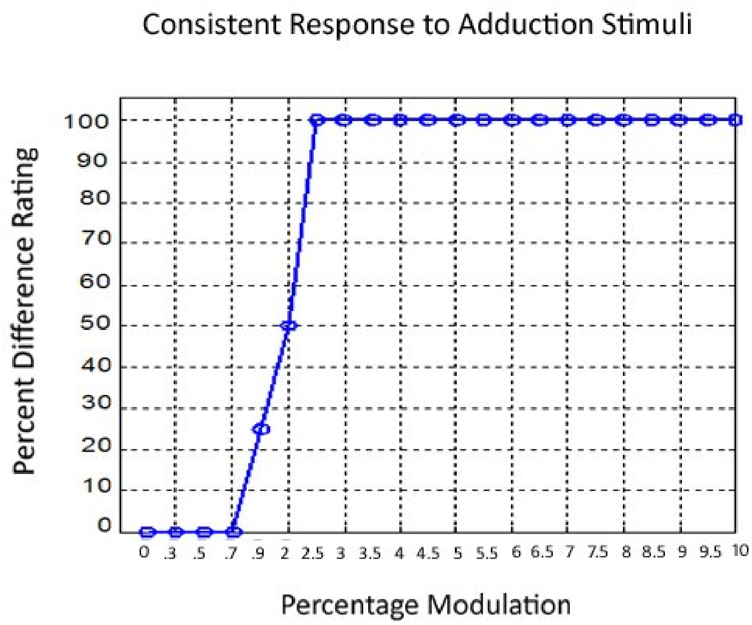

Figure 2A: Example response from one participant participating in adduction experiment. The threshold was quickly established and stayed at 100% ‘difference’ rating.

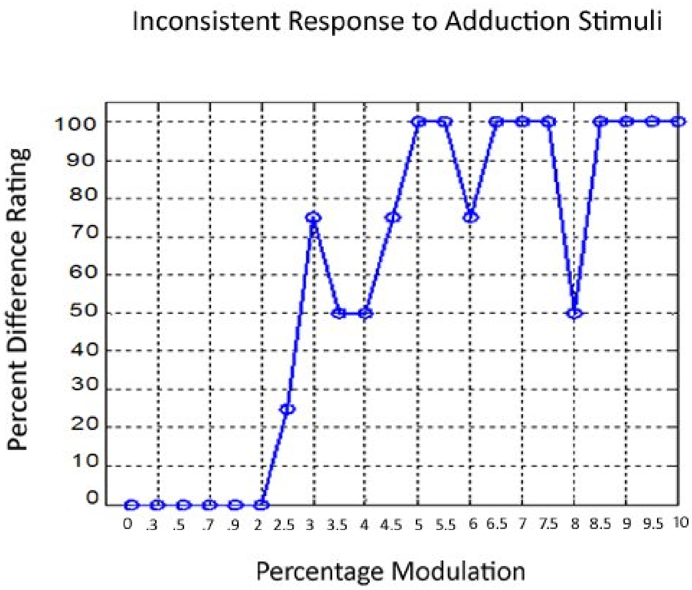

Figure 2B: Example response from one participant participating in adduction experiment. The threshold was met at 5.5% however the rating dropped below 75% confidence at 8%.

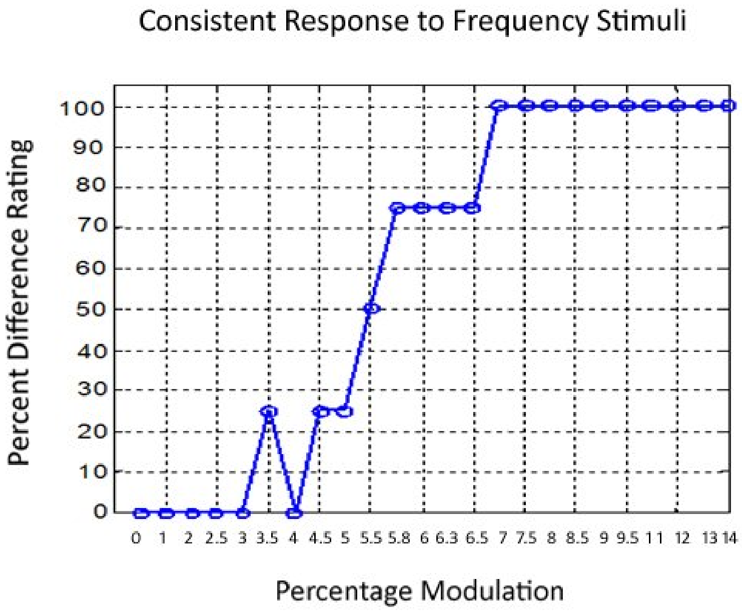

Figure 3A: Example response from one participant participating in frequency experiment. The threshold was met at 6.3% and stayed at 100% after 7%.

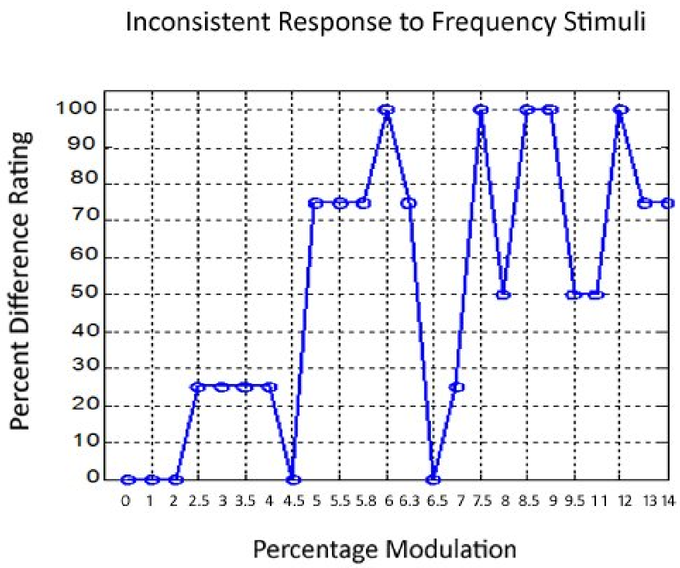

Figure 3B: Example response from one participant participating in frequency experiment. The threshold was met at 5.8% however dropped back down to 0% 'difference' rating at 6.5%. This means that the participant always rated the 0% modulation and 6.5% modulation stimuli as 'same'.

DISCUSSION

The purpose of this investigation was to investigate the contribution of modulation of the glottal width via vocal fold adduction/abduction compared to modulation of fundamental frequency via vocal fold length change modulation during phonation. That is, this study investigated the level at which naïve listeners could accurately detect the presence of vocal tremor by manipulating two different laryngeal parameters associated with production of a vocal tremor. The use of a computer-simulated vocal tremor afforded the opportunity to determine isolated degrees of laryngeal tremor and the degree to which tremor must be present in this part of the speech mechanism before naïve listeners could accurately identify its presence in the voice during sustained phonation of "ah."

The direct involvement of the larynx in converting the airstream from the lungs into sound for speech production leads to the hypothesis that modulation of fundamental frequency and intensity at the level of the larynx will be detected at low magnitudes (less than 10% modulation). As hypothesized, the averaged threshold plots (Figure 1A and1B) show that naïve listeners were able to detect vocal tremor using each method of modulating the larynx at low magnitudes (i.e. less than 10%).

Interestingly, there were clear differences between the results from the two different methods of modulating the laryngeal parameters. The threshold for glottal width modulation across 15 naïve listeners was 4% compared to the threshold of 8% for modulation of fundamental frequency via vocal fold length change. Further, 1/3 of the listeners in the fundamental frequency modulation group did not reach criteria for achieving threshold whereas all listeners achieved threshold identification of vocal tremor in the glottal width modulation group. Thus, it appears that listeners more easily and consistently identified the presence of vocal tremor when laryngeal modulation of glottal width contributed to the vocal tremor than when fundamental frequency was modulated.

Several considerations need to be explored from this research. First, this study demonstrates that within one component of the speech mechanism, differences in threshold for hearing vocal tremor can be demonstrated, depending on the nature of the modulation and its affect on the acoustic signal. Additional measures of the acoustic signal generated by these modulations and the ability to observe and measure the presence of tremor within the acoustic signal needs to be determined. Determination of possible differences in the acoustic signal associated with each type of modulation would help determine what acoustic features associated with vocal tremor are most easily detected by naïve listeners.

Naïve listeners were used in this study to determine the level at which the average listener, including physicians or other healthcare professionals without expertise in voice might hear the presence of vocal tremor in sustained phonation of an affected individual. Future work needs to investigate whether the thresholds found in this study are similar or different to those in individuals with expertise in voice. It might be predicted that voice experts would be better trained to hear the presence of vocal tremor at lower magnitudes of modulation than naïve listeners. However, this needs to be investigated to determine whether this is the case.

The current stimuli are not representative of the typical speech signal that naïve listeners are likely to hear produced by individuals with vocal tremor. It is more likely that individuals with vocal tremor will speak in sentences, or connected speech. Currently, clinical evaluation of vocal tremor requires perceptually determining the presence of vocal tremor by asking individuals to sustain phonation. This type of utterance allows easier detection of vocal tremor than occurs during connected speech due to the changes in the speech signal that may make it more difficult to hear vocal tremor. For example, the voice turns on and off during connected speech and disrupts the sustained ability to detect low frequency modulations in the signal that are perceived as vocal tremor. In addition, speech sounds are produced with various manners of production and the vocal tract changes shape resulting in changes in the formant peaks associated with different speech sounds. Thus, the energy level of the frequencies within the voice modify across different speech sounds in addition to the presence of voicing. Thus, it is expected that the threshold of identification of vocal tremor would increase in the context of connected speech. It would be of interest to determine whether the differences in threshold levels for hearing vocal tremor between the two methods of modulation in the current study are also different with connected speech utterances.

Another parameter not investigated in this study was that of the contribution of the fundamental frequency of the individual affected with the vocal tremor. That is, the current study investigated vocal tremor at a consistent fundamental frequency similar to that in an adult male. The computer model used for this research also utilized the vocal tract characteristics of a male. Adult males produce their voice at lower fundamental frequency and through a larger resonating chamber (vocal tract) than adult females. It is unclear whether the fundamental frequency or vocal tract size contribute to the output acoustics of vocal tremor such that it is easier or more difficult to hear in males than females. This issue needs to be considered in future research on this topic.

Finally, the speech samples in this study were not natural. Computer simulated signals were utilized to allow control over the variables that cannot be controlled in individuals affected by vocal tremor. More typically, it is expected that individuals affected by vocal tremor would exhibit tremor within several parts of the speech mechanism rather than in isolation. The contribution of this research is to systematically investigate the degree of contribution of various parameters contributing to vocal tremor to determine the degree to which each affect the perception of vocal tremor by listeners. The results of this research and future such studies will allow us to formulate hypotheses regarding affected parts of the speech mechanism for testing within speech produced by individuals with vocal tremor.

Overall, the clinical application of these findings predict that vocal tremor associated with laryngeal modulation of glottal width (vocal fold adduction/abduction) is more easily perceptible at a lower modulation magnitude to naive listeners than is modulation of fundamental frequency via vocal fold length changes. Based on these findings, it is predicted that individuals with tremor affecting vocal fold adduction may be identified earlier than individuals with tremor affecting vocal fold length associated with modulation of fundamental frequency, or pitch. Future research needs to investigate the associated acoustic affect of each method of modulation to determine the acoustic features associated easier detection of vocal tremor for each method. In addition, a comparison of threshold levels in naïve listeners needs to be compared to those from listeners with expertise in voice evaluation to determine the contribution of experience in listening to the voice to detection of the presence of vocal tremor.

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