Respiratory/Laryngeal Interactions During Sustained Vowel Production in Children

Donald S. Finan[1,2] *& Carol A. Boliek*[3]

[1]Department of Speech, Language, and Hearing Sciences,
[2]Center for Neuroscience, University of Colorado, Boulder, CO, USA
[3]Speech Pathology and Audiology, University of Alberta, Edmonton, Alberta, Canada
Don.Finan@colorado.edu

Abstract

Like many other rhythmic movements, respiratory behaviors arise from a central pattern generator (CPG). Modulation of the respiratory CPG function is requisite to generate the air pressures and flows essential for speech production. The emergence of voluntary respiratory system control and the coordination of respiratory and laryngeal structures likely parallels and contributes to the development of speech. Perturbation experiments have proven to be fruitful in exploring neural control of many CPG-modulated behaviors. Little is known about the development of respiratory control and the coordination between respiratory and laryngeal systems, especially for complex behaviors such as speech production. The purpose of this study was to investigate the interaction between laryngeal and respiratory responses to mechanical respiratory perturbation in children.

Index Terms: respiratory control, perturbation, children, sustained phonation

1. Introduction

Experiments in which environmental variables are altered, often by modifying sensory feedback (perturbation experiments) have proven to be fruitful in exploring how the brain controls many behaviors, including those behaviors that arise from CPGs [1], 2]. When investigating the neural control of speech, perturbation experiments are particularly useful [3], as animal models of orofacial movement are limited to non-speech behaviors (see [4]). One of the major obstacles of investigating the development of speech and related behaviors lies in the difficulty in performing perturbation experiments with children. In the absence of perturbation experiments, researchers must interpret descriptive data, which can only provide limited insight to neural control mechanisms (e.g. [5]).

Techniques used to perturb the respiratory system have been developed for the primary purpose of measuring various aspects of respiratory function or as a means to provide assisted ventilation, cardiopulmonary resuscitation, or lung secretion removal. Most techniques involve one of two approaches

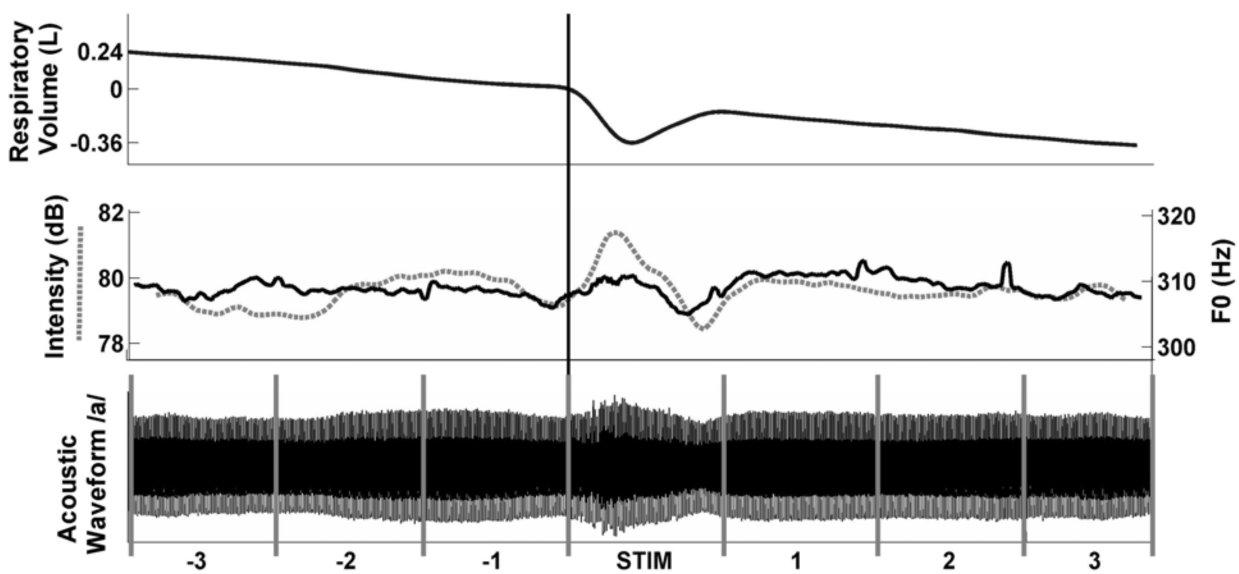

Figure 1 *Representative data illustrating a single stimulus trial and the seven 250 msec data blocks used for analysis. Stimulus onset is represented by the vertical line to the left of the "STIM" block. Respiratory volume change due to stimulation is shown on the top panel, with the onset of stimulation referenced to "0" Liters.*

including those applied to the airway opening (e.g., forced oscillation and flow interruption) and those applied to the external surface of the chest wall (e.g., rapid thoracic compression and high-frequency chest wall oscillation) [6, 7, 8]. Static perturbations such as trussing have been applied to the external surface of the abdominal wall in adults [9] and invasive perturbation has been used to study respiratory motor behaviors in animal models.

Recent reports have demonstrated that the laryngeal system utilizes auditory feedback mechanisms to maintain the stability of fundamental frequency and phonatory intensity upon acoustic feedback perturbation [10, 11]. During speech production, the respiratory and laryngeal systems must be elegantly coordinated in order to generate smooth, controlled speech acoustics. Unexpected perturbation to the respiratory system may thus be used to investigate the interaction between the respiratory and laryngeal systems.

The purpose of this study was to investigate laryngeal and respiratory responses to externally applied mechanical perturbations in children during vocalization. To this end, we employed a new stimulation technique for mechanically perturbing the chest wall in behaving children. Applying an external perturbation to the chest wall in allows us to take simultaneous respiratory kinematic and acoustic measurements during unencumbered speech.

2. Methods

2.1. Participants

Twelve children (9 males, 3 females; mean age = 9.1 years, sd = 1.31 years; mean vital capacity = 2.1 Liters, sd = 0.42 Liters) with no history of speech or respiratory disorders participated in this study. This study was approved by the University of Colorado Human Research Committee, and informed consent was obtained from each participant and their caregiver.

2.2. Procedures

Participants generated a series of steady sustained /a/ productions at comfortable loudness and fundamental frequency levels. Task instructions were to "say /a/ as steady as you can for as long as you can".

A series of controlled mechanical loads were delivered to the chest wall via a circumferentially applied pneumatic bladder. The bladder was actuated rapidly with a positive pressure pulse (approximate duration 150 msec) to produce a transient decrease in thoracic volume, thereby resulting in an increase in subglottal pressure and/or transglottal airflow (Figure 1).

Respiratory movements were transduced with a Respitrace inductive plethysmography system, with inductive bands applied under the pneumatic bladder. Participants performed isovolume maneuvers, and forced vital capacity was measured with an electronic spirometer (Vitalograph Micro 2110) in order to calibrate respiratory kinematics to lung volume. Speech acoustics were transduced by a forehead-mounted miniature microphone (Audio-Technica ATW-601) or headset microphone (Shure Beta 53). Stimulator bladder pressure was transduced with a SenSym miniature pressure sensor. Measured signals were sampled to computer with a 16-bit data acquisition system (AD Instruments PowerLab 16SP; sampling frequency = 20 kHz).

2.3. Data Analysis

Following data collection, acoustic data were inspected, and stimulus trials with audible artifact, voice breaks, and unstable fundamental frequency or intensity measures were discarded. Using custom software developed in Matlab (The Math Works, Inc.), acceptable trials were isolated and partitioned into seven contiguous 250 msec sections, with the fourth data block centered around the stimulus pulse (Figure 1).

Praat software (V.4.3.27) was used to calculate phonatory variables. Analyses include relative measures of phonatory fundamental frequency, intensity, and phonatory variability for each of the seven isolated data blocks.

3. Results

3.1. Intensity

Rapid positive pressure impulse stimulation to the thoracic and abdominal cavities during sustained /a/ phonation produced transient but significant increases in phonatory intensity [$F=26.69$, $p < 0.01$] (Figure 2) and phonatory intensity variability, as expressed by percent shimmer [$F = 18.98$, $p < 0.01$] (Figure 3). These changes in phonatory intensity variables did not appear to extend beyond the 250 msec STIM analysis block as both phonatory intensity and variability (shimmer) returned to pre-stimulus levels by the first measurement block following stimulation (vowel block "1").

The evoked increase in phonatory intensity suggests that the impulse perturbation yielded an increase in subglottal pressure.

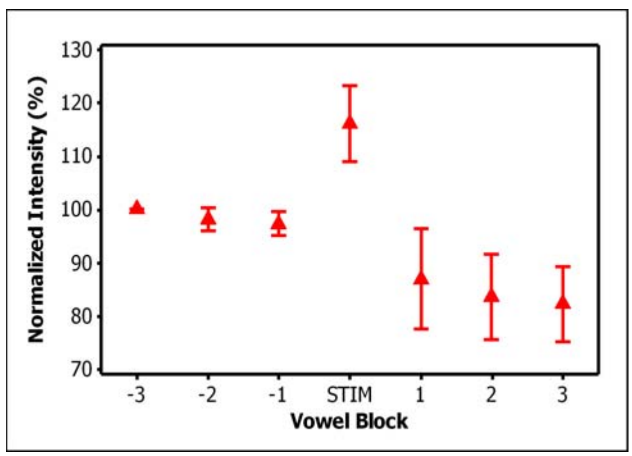

Figure 2 Normalized phonatory intensity by vowel data block. Data expressed as percent of the "-3" vowel analysis block.

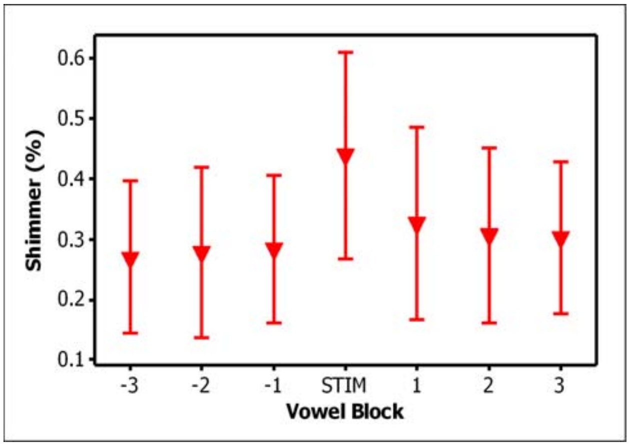

Figure 3 Phonatory shimmer by vowel data block.

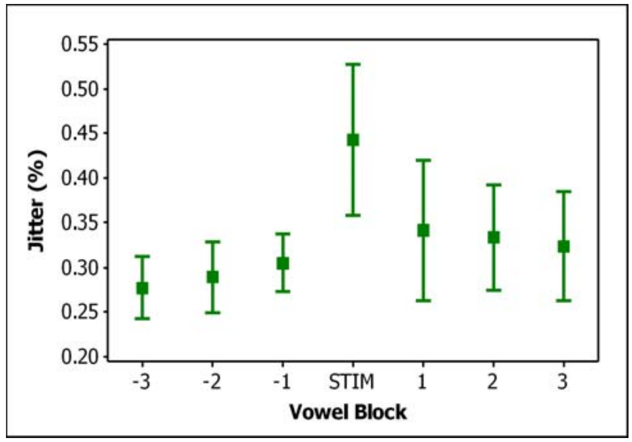

Figure 5 F_0 jitter by vowel data block.

3.2. Fundamental Frequency

Rapidly delivered positive pressure impulse stimuli presented during sustained /a/ production resulted in slight but nonsignificant transient increases in vocal fundamental frequency (Figure 4). In addition, phonatory variability as expressed by percent jitter increased significantly during stimulation [$F=8.14$, $p < 0.01$] (Figure 5). However, these changes did not appear to extend beyond the 250msec STIM measurement block, as fundamental frequency and jitter rapidly returned to near pre-stimulus levels by the first measurement block following stimulation (vowel block “1”).

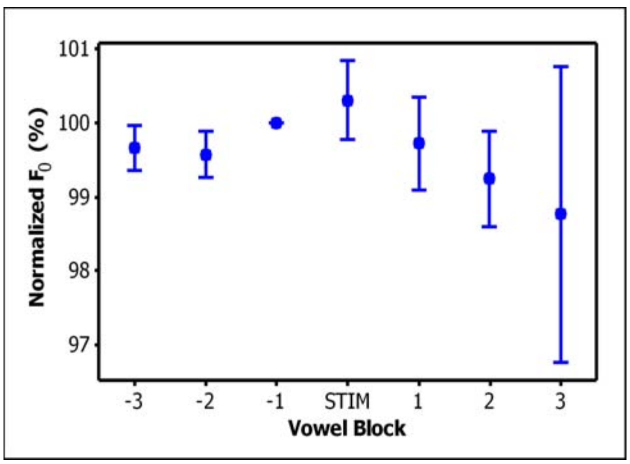

Figure 4 Normalized F_0 by vowel data block. Data expressed as percent of the “-1” block, immediately prior to stimulation.

4. Conclusions

One of the purposes of this project was to evaluate the effectiveness of a new system designed to perturb respiratory kinematics in behaving children. Previous studies in adults have employed forced oscillation techniques, either applied to the body surface with an actuated body plethysmograph (yielding subglottal pressure changes) or to the airway opening with an actuated air chamber coupled to the oral cavity (yielding supraglottal pressure changes) [12, 13, 14]. These techniques are physically restrictive and are not applicable for studies with young children. The technique presented here has proven to perturb the respiratory system during ongoing behavior in young children.

Forced oscillation respiratory perturbation studies in adults have demonstrated increases in vocal fundamental frequency associated with increases in subglottal pressure [12, 13, 14]. The current data demonstrate a strong increase in vocal intensity upon stimulation but only a modest (and nonsignificant) increase in fundamental frequency. However, variability of fundamental frequency was strongly increased upon stimulation. These results suggest that the pattern of fundamental frequency change seen in children due to transient increases in subglottal pressure are not as definitive as have been reported for adults. Thus, it is not clear if a consistent pattern of increased fundamental frequency with an increase in subglottal pressure is present for young children. High variability is characteristic of developing systems and may reflect instabilities in neural control mechanisms as well as underlying structural differences. Discrepancies in results between these adult studies and the current data are also possibly due to methodological differences, including the use of a sinusoidal stimulus train (forced oscillation studies) vs. the impulse stimuli used here.

Based on the time course, it is not likely that the responses seen here are the result of voluntary compensation to the perturbation. Therefore, the observed responses suggest the potential of two mechanisms: a CPG-modulated response (i.e. “reflexive”) or physical aeromechanical interactions (“passive”) within the larynx due to sudden increases in subglottal pressure. The current data do not allow for insight towards mechanism, however future studies using the current perturbation technology will focus on identifying the mechanism of response.

The current data provide a clear example of the interrelationship between the respiratory and laryngeal systems during sustained phonation. Rapid positive pulse mechanical stimulation to the chest wall resulted in transient decreases in thoracic cavity volume and yielded brief increases in transglottal airflow and presumably subglottal pressure as reflected by increased vocal intensity. Maintenance of a steady state phonation relies on uniform airflow from the respiratory system, and unexpected increases in airflow and/or subglottal pressure changes phonatory variables. As expected, unexpected increases in transglottal airflow and/or subglottal pressure yielded robust increases in phonatory intensity. However, fundamental frequency variability and intensity variability also demonstrated increases upon stimulation, reflecting the importance of a stable airflow/air pressure supply for maintenance of phonatory stability.

Instabilities in transglottal airflow and/or subglottal pressure may be manifest as instability in phonatory intensity and fundamental frequency. Due to the interdependence of the laryngeal and respiratory systems, investigations of phonatory variability must take into account measures of respiratory stability.

5. References

[1] Barlow, S.M., Finan, D.S., and Park, S.-Y., "Chapter 9: Sensorimotor entrainment of respiratory and orofacial systems in humans." In B. Maassen, W. Hulstijn, R. Kent, H.F.M. Peters, P.H.M.M. van Lieshout (Eds.), Speech Motor Control in Normal and Disordered Speech. Oxford University Press, 2004.

[2] Finan, D.S. and Barlow, S.M., "Intrinsic dynamics and mechanosensory modulation of non-nutritive sucking in human infants." Early Human Development, 52(2), 181-197, 1998.

[3] Smith, A., "The control of orofacial movements in speech." Critical Reviews in Oral Biology and Medicine, 3(3), 233-267, 1992.

[4] McFarland, D.H. and Lund, J.P., "An investigation of the coupling between respiration, mastication, and swallowing in the awake rabbit". J. Neurophys., 69(1), 95-108, 1993.

[5] Mizuno, K. and Ueda, A., "The maturation and coordination of sucking, swallowing, and respiration in preterm infants. J. Pediatrics, 142, 36-40, 2003.

[6] Desager, K., Marchal, F., and Van de Woestijne, K., "Forced oscillation technique, pp 355-378. In J. Stocks, P. Sly, R. Tepper, & W. Morgan (eds), Infant Respiratory Function Testing, New York: Wiley-Liss, Inc. 1996

[7] Hixon, T., "Some new techniques for measuring the biomechanical events of speech production: One laboratory's experiences." American Speech and Hearing Association Reports, 7, 68-103, 1972.

[8] Lausted, C. and Johnson, A., "Respiratory resistance measured by an airflow perturbation device." J. Physiological Measurement, 20, 21-35, 1999.

[9] Watson, P., and Hixon, T., "Effects of abdominal trussing on breathing and speech in men with cervical spinal cord injury." J. Speech Lang. Hear. Res., 44, 751-762, 2001.

[10] Burnett, T.A., and Larson, C.R., "Early pitch-shift response is active in both steady and dynamic voice pitch control." J. Acoust. Soc. Amer., 112(3), 1058-1063, 2002.

[11] Bauer, J.J., Mittal, J., Larson, C.R., and Hain, T.C., "Vocal responses to unanticipated perturbations in voice loudness feedback: an automatic mechanism for stabilizing voice amplitude." J. Acoust. Soc. Amer., 119(4), 2363-2371, 2006.

[12] Hixon, T.J., Klatt, D.H., and Mead, J. "Influence of forced transglottal pressure changes on vocal fundamental frequency." J. Acoust. Soc. Amer., 49, 105(A), 1971.

[13] Lieberman, P., Knudson, R., and Mead, J. "Determination of the rate of change of fundamental frequency with respect to subglottal air pressure during sustained phonation." J. Acoust. Soc. Amer., 45(6), 1537-1543, 1969.

[14] Rothenberg, M. and Mahshie, J. "Induced transglottal pressure variations during voicing." J. Phonetics, 14, 365-371, 1986.