Emergence and Refinement of Respiratory Chest Wall Intermuscular Coherence Associated with Speech and Non-Speech Tasks in Younger and Older Children

by

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Abstract

Introduction: There is limited information about the development of chest wall muscular control of lung volume and alveolar pressure for non-speech and speech tasks. The present study was the first in a series of studies aimed at achieving an in-depth understanding of intermuscular coherence of the chest wall for voluntary breathing during non-speech and speech tasks in typically developing children. Specifically, this investigation examined breathing kinematics, chest wall muscle activation patterns, and intermuscular coherence associated with non-speech and speech tasks varying on features of lung volume excursions and alveolar pressure targets. **Methods:** A mixed experimental design was employed on a cross-section of 15 younger children aged 6-9 years and 15 older children aged 13-16 years. Respiratory kinematics using variable inductance plethysmography along with intercostal and oblique muscular activity and intermuscular coherence derived from surface electromyography were analyzed for a series of tasks including: *(a)* vital capacity manoeuvres, *(b)* maximum duration phonation produced at conversational and perceived twice-conversational loudness, *(c)* sentence repetition produced at conversational and perceived twice-conversational loudness and *(e)* expiratory threshold loading (ETL) at maximal and submaximal expiratory pressures (MEPs). Data were collected in a single testing session. **Results:** The main findings were: *(1)* Breathing kinematic patterns for speech were similar between the two groups of children whereas breathing patterns differed for tasks involving larger alveolar pressure requirements or greater lung volume excursions; *(2)* Muscle activation amplitudes and intermuscular coherence differed between the two age groups for tasks involving speech production; and *(3)* Within groups, intermuscular control for task specificity was more precisely developed in the older group compared to the younger group of children. **Conclusion:** Consistent with previously documented changes in speech breathing kinematics

during development from childhood to adolescence, these data provide evidence that children also are undergoing age related changes in intermuscular coherence for speech breathing. Intermuscular coherence appeared to be task specific for both groups of children but more so in the older children. Based on strength of peak coherence, older children exhibited increased intermuscular coherence and greater muscular coordination during speech breathing in comparison, younger children who exhibited lower intermuscular coherence had a lower amount of muscle coordination. Both older and younger children displayed decreased muscle coordination for non-learned, non-speech tasks requiring maximal lung volume and/or pressure generation (i.e., maximum performance tasks and expiratory threshold loading). Further research is required to classify the relationship between strength of intermuscular coherence and distribution of the signal through the corticospinal tract. The results of this study may contribute to informing voice and speech treatment interventions targeting children and adolescents with neurogenic communication disorders involving the respiratory-laryngeal subsystems.

Preface

This thesis is an original work by Darian Bremmekamp. The research project, of which this thesis is part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name: *Emergence and Refinement of Respiratory Chest Wall Intermuscular Coherence Associated with Speech and Non-speech tasks in Children and Adolescents*; Pro00054045; 5 January 2015.

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Introduction and Literature Review

Speech requires the coordination of multiple subsystems including respiratory, laryngeal, pharyngeal-nasal and oral-articulatory (Hixon et al., 2014). The respiratory subsystem for speaking is the focus of the present study. Whereas breathing for ventilation is a natural process under autonomic control, speech breathing requires voluntary control (Bunn et al., 1971) and occurs on the expiratory limb of the breathing cycle (Hixon et al., 2014). Connected speech is composed of two classifications of speech sounds: voiced (addition of phonation via vocal fold vibration to create sound) and voiceless (no vocal fold vibration; solely production of sound via airflow through or across articulatory movements of the tongue, lips, mouth and teeth). Speech produced at conversational loudness requires the maintenance of tracheal pressures somewhere between 5 and 10 cmH_2O even though lung volume is decreasing across the breath group. Thus, the addition of muscular pressure is needed from rib cage and abdominal expiratory muscles. Adults speak in the midrange of their vital capacity (VC) using between 10 and 20 percent of their VC per expiratory breath group and have inspiratory durations that are shorter and expiratory durations that are longer than those observed during resting breathing (Hixon et al., 1976). In contrast, children are much more variable relative to where in their vital capacities they initiate speech and how much air they use when speaking (Boliek et al., 1996, 1997, 2009).

A large compilation of work describes the emergence and refinement of speech breathing in children from birth to 6 years of age (Boliek et al., 1996, 1997, 2009) and children ages 7, 10, 13 and 16 years (Hoit et al., 1990; Stathopoulos and Sapienza, 1997). These studies have provided a foundation for future work that advances our understanding about chest wall muscular control for non-speech and speech tasks and its development.

Whereas the emergence and refinement of speech breathing kinematics has been well documented, little is known about the development of muscular control of the chest wall for executing non-speech and speech tasks varying in lung volume excursions and alveolar pressure requirements. A number of neurodevelopmental disorders result in deficits in neuromuscular control in children and adolescents that can result in speech motor control impairment (Duffy, 2013). Knowledge regarding developmental changes associated with muscular control of the chest wall in typically developing children will serve to advance efficacious voice and speech treatment interventions for children who have neurogenic communication disorders involving the respiratory-laryngeal subsystem.

Speech Breathing

Speech breathing requires refined motor control and involves progression through periods of emergence, refinement and adaptation throughout the lifespan (Boliek et al., 2009; Hoit et al., 1990). Of interest in the present study, is the period of refinement, which begins around 18 to 36 months and continues throughout childhood and into adolescence. This developmental timeframe is characterized by continued growth of the breathing apparatus and increased complexity of spoken language (Hoit et al., 1990). The largest differences in speech breathing appear between the ages of 7 and 10 years (Hoit et al., 1990). Findings from previous research suggest that at age 7 years, speech breathing is in the process of developing into the more refined adult model, and that by age 10 years and prior to the onset of puberty, the major maturational changes in speech breathing have been completed (Hoit et al., 1990). By age 10 years, children speak in the midrange of their vital capacity (VC), use between 10 and 20 percent of their VC per expiratory breath group, and use approximately 80% rib cage contribution to lung volume excursions (Hoit et al., 1990; Stathopoulos and Sapienza, 1997). Prior to age 10 years, children use a wide range of lung volumes for vocalizations and speech (Boliek et al., 1996, 1997) and prior to age 7 (Hoit et al., 1990) may utilize a wide range of displacements of the rib cage and abdomen for lung volume excursions (Boliek et al., 1997). No relevant sex differences have been found in speech breathing behaviour at any age (Boliek et al., 1996, 1997, 2009; Hoit et al., 1990).

Most of what we know about speech breathing comes from chest wall kinematics and speech acoustic measurements (Boliek et al., 1996, 1997, 2009; Hoit et al., 1990; Stathopoulos and Sapienza, 1997), with only a few studies utilizing surface electromyography (sEMG) techniques to measure chest wall muscle forces associated with speech breathing activities (Clair-Auger et al., 2015; Hixon and Weismer, 1995; Hoit et al., 1988; McFarland and Smith, 1989; Watson et al., 1989). For example, active expiration uses the rib cage and abdominal muscles and occurs during voluntary exhalations like those used for speech production (Silverthorn, 2013). In addition, abdominal muscles are continuously active during resting breathing and generally active during speech (Hoit et al., 1988). Moreover, non-speech and speech tasks requiring higher tracheal pressures are accomplished with the recruitment of greater chest wall muscular activity (Clair-Auger et al., 2015; Hixon and Weismer, 1995; McFarland and Smith, 1989; Watson et al., 1989). Similarly, with increased tracheal pressure, higher lung volumes at utterance initiation and the use of larger lung and rib cage volume excursions have been documented (Stathopoulos and Sapienza, 1997). Voluntary motor control for speech breathing can best be assessed through respiratory kinematics as described below.

Speech Breathing Kinematics

Kinematic analysis of the chest wall has proven to be a powerful method of studying speech breathing (Hixon, 1982). The kinematic method involves treating the chest wall as a two-part system comprised of the rib cage and abdomen and together they displace a volume equal to that of the lungs (Watson, 1979). Volume displacements associated with the rib cage and abdomen contributions are measured by detecting changes in the anteroposterior diameters of each (Hixon, 1982). Variable inductance plethysmography (Respitrace) has been successfully used to measure chest wall kinematics in children (Boliek et al, 1996). This method involves the use of transduction bands, which encircle the rib cage and abdomen separately and sense changes in diameter. The average of an infinite number of cross-sections through the height of a band is calculated and measures chest wall size (Boliek et al., 1996; Watson, 1979). After calibration (i.e., isovolume manoeuvres and volume assessed at the airway opening), signals from the rib cage and abdomen can be summed to reflect displacement of the lung (Boliek et al., 1996, 1997, 2009; Hixon, 1982).

The advantage for using inductance plethysmography for the evaluation of speech breathing kinematics is that it leaves participants relatively unencumbered thus, speech breathing behaviours represent a more naturalistic phenomenon (Boliek, et al., 1996). Kinematic measurements derived include: lung volume initiations, terminations and excursions; percent rib cage contribution to lung volume excursions; inspiratory and expiratory durations; among others. Boliek et al. (1996, 1997 & 2009) found that in children, lung volume events for vocalization and speaking occurred across a wide range of the VC. However, relatively stable and quick inspiratory durations were observed in both the emergence (5 weeks to 36 months of life) and the early refinement periods (4 to 6 years of age) of speech breathing. Younger children exhibited smaller absolute lung volume excursions (Boliek et al, 2009) than older children and adolescents (Hoit et al, 1990), however they exhibited more air expenditure per syllable and demonstrated instances of non-vocal expirations. Most notably, children in the early refinement period exhibited variability in their percent rib cage contribution to lung volume excursions, which indicates experimentation with various chest wall displacement patterns for speaking (Boliek et al., 2009). In contrast, older children use primarily rib cage contributions to lung volume excursions demonstrating more adult-like control (Hoit et al., 1990). Overall, previous speech breathing kinematic literature has identified the periods of emergence and refinement of speech breathing and form the basis for the present investigation, which was designed to further advance our understanding of emergence and refinement of speech breathing via intermuscular coherence of speech breathing in typically developing children.

Intermuscular Coherence

Frequency analyses of biological signals (e.g., sEMG, EEG) is a useful way to analyze neuronal synchrony (Grosse et al., 2002). Coherence, as defined by Grosse et al. (2002), is the principal measure of the linear dependence or correlation between two signals in the frequency domain. Corticomuscular coherence occurs between the motor cortex and muscle and is measured as the oscillatory coupling between motor elements of the central nervous system and EMG discharge (Grosse et al., 2002). The coupling of cortical activity with output muscle activity has previously been demonstrated by magnetoencephalography (MEG) (Conway et al., 1995; Salenius et al., 1997) or surface electromyography (EEG) (Mima et al., 2000). Similarly, recent studies have utilized intermuscular coherence, the oscillatory coupling between EMG signals of opposing muscles co-activated in the same task (Kilner et al., 1999). EMG-EMG analysis is performed using sEMG on muscle pairs that are separated and would likely have a phase difference (Grosse et al., 2002). Correlated oscillations in two EMG signals arise from a tendency for motor units to be activated synchronously, thus intermuscular coherence is a noninvasive measurement of muscle coordination between disparate muscles (Bruce & Ackerson, 1986; Boonstra, 2013).

An ongoing discussion exists surrounding the use of intermuscular coherence as a measure of cortical drive (Boonstra, 2013). Corticomuscular and intermuscular coherence may give comparable information about descending cortical drive even though they are measured from different pairs of signals (Grosse et al., 2002). However, to date there has been no report of a direct relationship between the EMG signal from a muscle and the EEG signal from the motor cortex during a "non-rhythmic" dynamic muscle contraction (Maurer et al., 2013). Further evidence is needed to prove that oscillatory coupling between EMG-EMG signals during a dynamic contraction are coherent with brain waves as measured via more direct methods (e.g., EEG or MEG) (Maurer et al., 2013). A number of studies (Hansen et al., 2005; Norton & Gorassini, 2006; Fisher et al., 2012) have contributed evidence that intermuscular coherence represents descending neuromuscular modulation through the corticospinal tract. The drive to coordinated muscles, likely has output originating largely from the motor cortex (Grosse et al., 2002), with evidence to support additional subcortical influence as found by the effects of the basal ganglia on cortical areas in patients with Parkinson disease (Salenius et al., 2002). While it is clear that corticospinal tract innervation from supraspinal regions to the spinal cord is essential to measures of intermuscular coherence, the relationship between corticospinal tract integrity and strength of intermuscular coherence in developing children has not been documented. Thus, hypotheses can be made with regards to descending oscillatory drive through the corticospinal tract, but conclusions cannot be drawn.

It is known that the central nervous system drives muscle discharges at a number of frequencies (Brown, 2000). Activities in the *beta* (15-30 Hz) and low *gamma* (30-60 Hz) bands are predominantly driven by the motor cortex (Brown, 2000; Grosse et al., 2002), whereas activities in the 2-6 Hz and 6-12 Hz bands have an unknown origination. Some speculate that coherence in these frequency bandwidths represents drive from the olivary-cerebellar system, but also have been linked to the primary motor cortex for certain tasks (Marsden et al., 2001; Grosse et al., 2002). Activity in the 60-110 Hz band has been linked to brainstem control through recordings of high frequency oscillations from central pattern generators (Denny & Smith, 2000).

The frequency in which intermuscular coherence occurs may be strength dependent (Andrykiewicz et al., 2007; Brown et al., 1998; Chakarov et al., 2009) or skill dependent (Semmler et al., 2004). However, most coherence studies have been done on muscles of the limbs and only a few investigations have used this measure in the context of understanding intermuscular coherence for speaking (e.g., Tomczak et al, 2013). Three studies have characterized intermuscular coherence associated with speech and non-speech tasks. Stepp et al. (2011) showed that intermuscular coherence values were much lower for complex speaking tasks (i.e., digits repeated backwards) relative to typical speech productions. Smith and Denny (1990) observed similar intermuscular coherence in the 20-60 Hz range for speech tasks and deep breathing tasks. In addition, Tomczak et al. (2013) found that intermuscular coherence was greater for breathing tasks occurring in the midrange of VC than those covering the entire range of VC. While we know that the amount and frequency of intermuscular coherence can be dependent upon the strength of the task and the skill level required for the task, the impact of developmental changes on muscular coordination for speech breathing remains unknown.

Rationale

Previous research on breathing for speech, done by Boliek et al. (1996, 1997, 2009), Hoit et al. (1990) and Stathopoulos and Sapienza (1997) provided the foundation for the present investigation. Currently, there is no clear understanding of the developing chest wall muscular activity associated with varying lung volume and alveolar pressure requirements for voluntary breathing associated with non-speech and speech tasks. Note that we refer to *alveolar pressure* as the pressure in the lung and airway and refer to *tracheal pressure* only in instances where we made indirect measures to subglottal pressures (Smitheran and Hixon, 1981). Given the previously documented changes in breathing involved in the production of speech, it is relevant to examine the assumption that children also will be undergoing changes in the intermuscular coherence of speech breathing. Therefore, it is important to obtain data on muscular activity related to non-speech and speech breathing from healthy children and adolescents to provide an initial foundation from which to draw conclusions about the development of speech sub-systems. Moreover, understanding intermuscular coherence for speaking tasks can provide guidance when informing voice and speech interventions targeting children and adolescents with neurogenic communication disorders specifically involving the respiratory-laryngeal subsystems. In this context, the present study was conducted to elucidate the nature of intermuscular coherence for non-speech and speech tasks in younger and older children. Specifically, intermuscular coherence of the chest wall and the effects of developmental changes on this measure were studied by controlling the age of participants and tasks varying in lung volume and alveolar pressure requirements.

Purpose

Research Question

What is the pattern of voluntary motor control of breathing as assessed by chest wall muscle activation patterns and intermuscular coherence associated with speech and non-speech tasks varying in lung volume and alveolar pressure requirements in younger and older children?

Hypotheses

(1) Based on previous speech breathing literature we hypothesized that younger and older children would exhibit different absolute lung volume initiations. *(2)* We hypothesized that whereas older children would have relatively stable lung volume terminations and excursions younger children would exhibit greater variability. *(3)* We hypothesized that younger children would present variable contributions of the rib cage and abdomen across tasks relative to their more stable older counterparts. *(4)* Based on the developmental literature we hypothesized that younger children would exhibit greater muscle activation amplitudes compared to older children. *(5)* We hypothesized that younger children would exhibit intermuscular coherence in the 15-59 Hz frequencies indicative of similar muscle coordination patterns for all tasks regardless of volume and/or alveolar pressure targets. *(6)* In contrast, we hypothesized that older children would exhibit changes in intermuscular coherence in the 15-59 Hz frequencies based on task-specific features of skill and strength.

Experimental Design

The present study employed a mixed subjects research design. Two age groups (6-9 year olds; 13-16 year olds) were evaluated on each of six breathing and muscular variables including: *Lung Volume Events* [Lung volume initiation (LVINIT in mls), termination (LVTERM in mls), excursion (in percent predicted VC, PVCLVE), and percent rib cage contribution to lung volume excursion, (PCTRC)] and *Chest Wall Muscular Events* [amplitude (in percent maximum voluntary contraction, %MVC) and intermuscular coherence (correlation above 95% confidence interval)]for the combined *beta* and low *gamma* bandwidths (15-59 Hz) across a series of eight breathing tasks. These included: VC, maximum duration phonation at conversational loudness (PH), maximum duration phonation at perceived-twice conversational loudness (PH2), sentence repetition (speech) at conversational loudness (SP), sentence repetition (speech) at perceived twice-conversational loudness (SP2), maximum expiratory pressure 100% (MEP100), expiratory pressure at 20% (MEP20), and rest breathing (RB) as a baseline.

Selection of non-speech and speech tasks. Each of the tasks were specifically selected to systematically manipulate lung volume excursions and alveolar pressure requirements. VC maneuvers were selected because they represent a maximum lung excursion with low to nil maintenance of alveolar or tracheal pressures. Maximum duration phonation required maximum lung excursion while maintaining alveolar pressures between 5 and 10 cmH_2O. Maximum duration phonation X2 required maximum lung excursion while maintaining alveolar pressures between 10 and 20 cmH_2O. Speech was produced in the midrange of VC, required excursions between 10 and 20 %VC, and alveolar pressures between 5 and 10 cmH_2O. Speech X2 was produced in the midrange of VC, required excursion of approximately 30 to 50 %VC, and alveolar pressures between 10 and 20 cmH_2O. The MEP100 task required a maximum inspiration followed by excursions requiring maximum expiratory threshold loading (ETL) with little lung volume loss. The lowest ETL task (MEP20) required a maximum inspiration followed by excursions requiring alveolar pressures lower than needed for MEP100 but higher than PH2 or SP2. Resting breathing served as a baseline task. Experimental task properties can be seen in *Table 1.*

Table 1. Experimental tasks selected to manipulate lung volume excursions and alveolar pressures. Included are their associated lung volume excursions, location of lung volume events relative to vital capacity and presumed alveolar or tracheal pressures.

Task	Lung Volume Excursion (%VC)	Location Relative to VC	Tracheal-Oral Pressure (cmH_2O)
Rest Breathing (RB)	10[a]	Midrange	0[a]
Vital Capacity (VC)	90-100[a,b]	Full range	0[a]
Maximum Phonation (PH)	90-100[b]	Full range	5-10[g]
Maximum Phonation X2 (PH2)	90-100[b]	Full range	10-20[h]
Speech (SP)	10-20[c,d]	Midrange	5-10[g]
Speech X2 (SP2)	50[e]	Midrange	10-20[h]
Maximum Expiratory Pressure 100% (MEP100)	15[f]	Midrange	90[f]
Maximum Expiratory Pressure 20% (MEP20)	80[f]	Midrange	40[f]

Note: Adapted from [a]Hixon, Weismer & Hoit (2014); [b]Solomon, Garlitz & Milbrath (2000); [c]Hoit et al., 1990; [d]Hixon, Mead & Goldman (1976); [e]Russell & Stathopoulus (1988); [f]Bremmekamp et al., (2015); [g]Ladefoged (1963); [h]Stathopoulos & Sapienza (1997)

Method and Procedures

Participants

Fifteen typically developing younger children between the ages of 6 and 9 years (10 females, X = 7.9 years, SD = 0.9 years) and fifteen typically developing older children between the ages of 13 and 16 years (11 females, X = 14.8 years, SD = 1.0 year) were recruited. Participant demographic information is presented in Table 2.

Table 2. Demographics of 30 study participants of two age ranges.

	Sex	Age Range (years)	Height (cm)	Weight (lbs)
Young	10f 5m	6-9	126.83 (8.49)	27.03 (5.73)
Old	11f 4m	13-16	169.55 (6.98)	66.13 (9.98)

These two age groups were chosen because children are shown to have adult-like speech breathing, with respect to lung, rib cage, and abdominal volume events by age 10 years (Hoit et al., 1990). Additionally, children around age 7 years are basically adult-like in phonological skill (identify, blend, segment and manipulate sounds) but are still developing at a motoric level (Kent, 1976), whereas adolescents around age 16 years have completed puberty and can be assumed to be adult-like in their motoric skills (Hoit, et al. 1990). By testing these two age ranges, we were able to contrast child-like speech with adult-like speech. All participants were of average height and weight for their age range, had normal hearing, language, cognition, average physical activity levels, a negative history for chest wall surgery and overall good health. Written and informed consent and assent were obtained for each participant in this study which is approved by the University of Alberta's Health Research Ethics Board and conforms to the standards of the Declaration of Helsinki (World Medical Association, 2008).

Equipment and Measurements

Video recordings were made of each test session to be certain that only data collected when participants were in stable, upright posture were used for off line analyses. Acoustic data was acquired using a small microphone (SHURE MX-185) placed on the forehead, 10 cm from the mouth, amplified (M-Audiobuddy Pre-Amplifier) and digitally recorded at a sampling rate of 44.1 kHz on a laptop computer using TF32 Software (Milenkovic, 2001). In addition, online vocal sound pressure level (dB SPL) was measured for speech and phonation tasks to quantify experimental loudness targets. Calibration of the audio signals was done via the presentation of a 440 Hz tone presented at the mouth (KORG Orchestral Tuner, OT-12) and a sound level meter (ExTech Sound level meter, 407764) in line with the forehead-mounted microphone. Sound level in dB SPL was recorded for a 10 second sound sample and used in the calculation of vocal loudness in SPL during off line acoustic analyses.

Chest wall kinematics were obtained using variable inductance plethysmography (Respitrace, Ambulatory Monitoring Company, NY). Transduction bands were placed around the rib cage and abdomen (as described in Boliek et al., 1996). The rib cage band was placed with its upper edge just below the axillae and its lower edge just below the nipples, and the abdomen band was placed with its upper edge just below the costal margin and its lower edge just above the iliac crests (Boliek et al., 1996).

sEMG recordings were done on the right side of the chest wall from the intercostal and oblique muscle regions. Two electrodes (Kendal Soft-E H69P, Tyco Healthcare Group, Mansfield, MA) were positioned 2 cm apart (center-to-center) and oriented parallel to fiber direction for the muscle over the 6th intercostal space and oblique regions. Intercostal electrodes were placed ventrally 8-10 cm from midline, and oblique muscle electrodes were placed midway between the anterior superior iliac spine and caudal border of the rib cage. The electrode placement protocol optimized ventral-dorsal EMG location (Tomczak et al., 2013). sEMG signals were amplified (Grass P511, Quincy, MA), and band-pass filtered (3-3000 Hz).

Expiratory threshold loadings (MEP100, MEP20) were measured with a custom-modified resistor system (i.e., oral resister with variable settings) attached to a sterilized mouthpiece. A small pressure tube housed within the resistor and attached to a differential pressure transducer (Validyne model DP45-14) and amplified (Validyne model CD15) was used to sense oral pressure. Pressures were calibrated against a digital monometer in cmH_2O (Omega Engineering HHP-90 Monometer). Speech and phonation pressures were estimated by measuring expiratory pressure at the lips via a small pressure tube while children produce a sequence of /pi/ at a rate of 1.0 syllable per second at conversation and perceived twice-conversational loudness levels (Smitheran and Hixon, 1981). Volume calibrations were accomplished via collecting breathing samples via a sterile mouthpiece attached to a pneumotachometer-variable pressure transducer and amplified (Validyne model DP45-14; Validyne model CD15). Volume was calibrated against a 3-liter syringe (Hans Rudolph). All physiological signals were transduced and displayed in real time and simultaneously acquired (sampling rate = 10 KHz) using an eight-channel digital recorder (A R Vetter Co, Rebersburg, PA) as well as Power Lab (ADInstruments, Colorado Springs, CO).

Procedures and Experimental Tasks

Participants underwent a single test session in Dr. Boliek's Laboratory, lasting approximately one hour. After obtaining written and informed consent and assent, participants were seated in a chair and fitted with sEMG electrodes, Respitrace transduction bands, and a forehead mounted microphone. Rest breathing captured by the mouthpiece (nose clips were used to seal off the nasal passage) and isovolume manoeuvres were recorded to be used for calibration of the chest wall. Vocalizations of /pi/ at perceived conversational (PI) and perceived twice-conversational (PI2) loudness were taken to later estimate tracheal pressure during speech and phonation tasks.

Participants were then asked to perform three to five usable trials of each of the prescribed tasks. VC manoeuvres were accomplished using the standard procedures outlined by the American Thoracic Society (ATS). Next, participants were instructed to, *take a big breath in and say ah for as long as possible* (PH). Then participants were asked to repeat the same task only this time phonating at perceived twice-conversational loudness (PH2). An exemplar of data collection using LabChart7 (ADInstruments, Colorado Springs, CO) is shown in *Figure 1.* Participants were then instructed to *take a big breath in and blow as hard as possible for 5 seconds*, against the custom-modified resistor held in place at the mouth with the nose occluded via nose clips (MEP100). Following this, a second resistor was connected to the mouthpiece (MEP20) and children were given the same instructions as for MEP100. Speech tasks involved sentence repetitions of, *Buy Bobby a puppy*, *The blue spot is on the key*, and *The potato stew is in the pot*, at conversational (SP) and perceived twice-conversational (SP2) loudness.

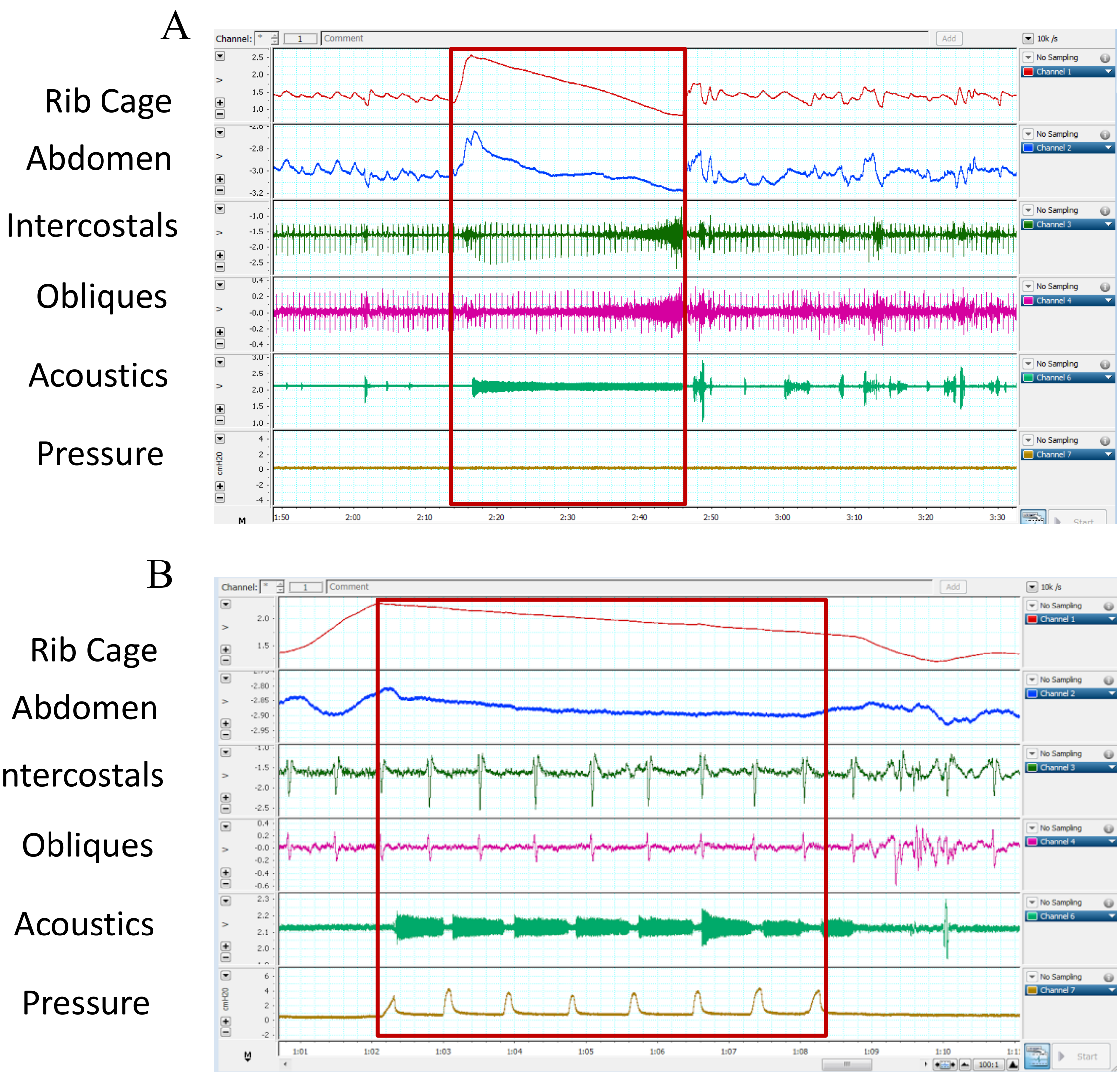


Figure 1. Exemplar of simultaneous data collection using the PowerLab acquisition protocol during a maximum phonation task (A) and expiratory pressure measurement utilizing a sequence of /pi/ (B). Starting from the top tracing, rib cage and abdomen kinematic signals are shown followed by sEMG signals for the intercostal and oblique muscle groups. The next signal represents the acoustic signal (10 cm mouth-to-mic distance). The bottom signal is pressure sensed from the oral pressure tube. The red box in panel **A** shows the upward and downward deflection of the rib cage and abdomen signals representing inspiration and expiration; respectively. Increased muscle activation is demonstrated by periods of greater amplitude, as seen at the end of phonation. The red box in panel **B** encompasses the expiratory breath group during the repeated production of /pi/ on a single breath. As can be seen on the bottom pressure tracing, increases in oral pressure are associated with the initiation of the bilabial /p/.

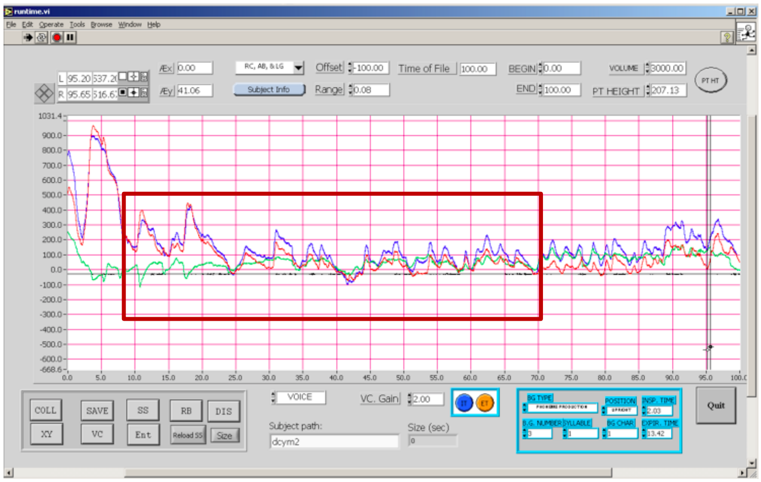
Analysis

Data Analysis.

Wherever possible, at least three trials of each task were analyzed for kinematics, coherence, sEMG and acoustics. Trials that did not meet protocol guidelines were excluded from analyses.

Kinematic analysis was done using the custom software program in LabView (National Instruments, Austin, TX) as shown in *Figure 2.* Calibration of lung volume to within 5% correct estimation was done using the recorded syringe volume of 3000 mLs, isovolume manoeuvres, and volumes acquired during rest via mouthpiece-pneumotachometer-transducer. Kinematic analysis was used to quantify respiratory support (the driving force) for non-speech tasks and speech tasks. It included: (a) lung volume initiation, termination and excursion, (b) percent vital capacity, (c) percent rib cage contribution to lung volume excursion and (d) inspiratory and expiratory durations. The expiratory limb for each task was analyzed using end expiratory level (EEL) as a reference.

A



B

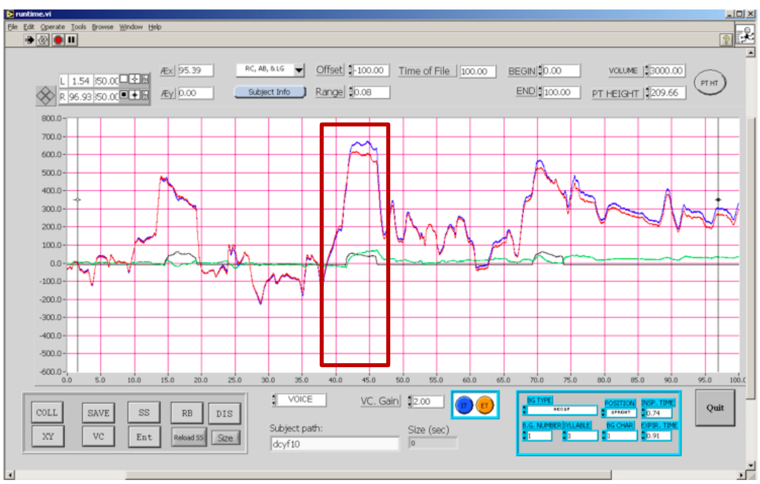


Figure 2. Exemplar of output from kinematic analysis using the LabView acquisition protocol for speech (A) and maximum expiratory pressure (MEP100) (B). Red, green and blue tracings represent the kinematic signal from the rib cage, abdomen, and calibrated lung volume; respectively. Time (s) of sample taken and volume (mL) are represented on the *x* and *y* axes; respectively. Rib cage, abdomen and lung volumes displacements are either in the inspiratory (upward direction) or expiratory (downward direction). Black lines represent speech (**A**) or pressure (**B**). The red boxes represent typical speech breathing (**A**) and chest wall kinematics associated with breathing against an expiratory threshold (i.e., MEP100 in this case) (**B**).

sEMG activity was analyzed on the expiratory limb of each breath group for each task by identifying and selecting from the onset of expiration to the termination of expiration. Several measurements were made on the sEMG signals (MATLAB, MathWorks, Natick, MA) including: (a) average amplitude [derived from averaged peak amplitudes normalized on maximum voluntary contraction (MVC)], and (b) peak coherence [calculated as the frequency domain equivalent of cross-correlation of the sEMG-sEMG (i.e. intercostal-oblique)].

Calculations. Intermuscular coherence equation:

$$MSC\ |Cxy(w)|^2 = \frac{\left|\overline{Gxy(w)}\right|^2}{\overline{Gxx(w)}\ \cdot \overline{Gyy(w)}}$$

Where MSC is the magnitude squared coherency (coherence), Gxx(w) and Gyy(w) are the averaged power spectra of x and y throughout the segments for a given frequency w, and Gxy(w) is the averaged cross power spectrum of signals x and y at frequency w (Halliday et al. 1995; Rosenberg et al. 1989). Average number of segments analyzed and resulting average total duration of analyzed tasks can be found in Table 3.

Table 3. Average number of segments analyzed for each task based on a time and sampling rate of 10 KHz with accompanying average total analyzed task duration.

	Task	MEP100	MEP20	PH	PH2	RB	SP	SP2	VC
Young	Average Number of Segments	64.20 (11.25)	71.07 (13.59)	107.4 (45.97)	112.73 (46.38)	52.60 (14.52)	56.67 (8.36)	58.20 (9.94)	57.07 (21.15)
	Average Task Duration (s)	26.56 (4.66)	29.33 (5.57)	44.18 (18.81)	46.38 (19.02)	21.77 (5.95)	23.49 (3.39)	23.98 (4.10)	23.54 (8.63)
Old	Average Number of Segments	62.87 (7.89)	72.00 (8.25)	170.93 (46.24)	158.20 (46.55)	60.53 (16.61)	58.67 (11.34)	73.47 (18.72)	113.07 (52.67)
	Average Task Duration (s)	25.97 (3.26)	29.65 (3.40)	70.20 (18.98)	64.98 (19.11)	25.02 (6.86)	24.21 (4.66)	30.28 (7.65)	46.53 (21.56)

An exemplar of coherence data for a younger and older participant is shown in *Figure 3*. Intermuscular coherence was determined using open access MATLAB scripts (www.neurospec.org) (Halliday et al., 1995). Collected data were passed through a Tukey window to reduce erroneous high-frequency signals at the borders of adjoining breath trials, concatenated and rectified. A 95% confidence limit was used to indicate the level at which coherence is significant. MATLAB was used for all sEMG analyses.

A. B.

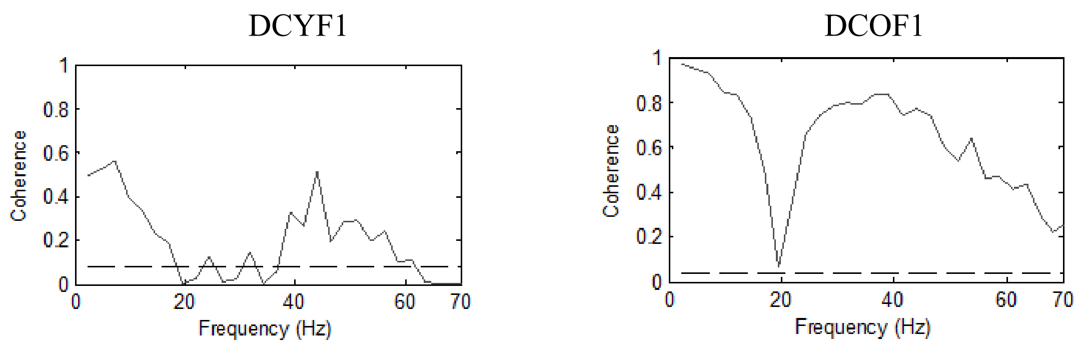


Figure 3. Exemplar of IC-OB intermuscular coherence for an 8-year-old girl (A.) and a 15-year-old girl (B) during a speaking task produced at twice-conversational loudness. The two panels represent the coherence spectra calculated between the intercostal and oblique muscles from sEMG. Strength of coherence (amplitude) and frequency (Hz) are represented on the *y* and *x* axes; respectively. Significant coherence is represented by the part of the waveform above the 95% confidence interval (dashed horizontal line).

Phonation and speech tasks were acoustically analyzed to determine average loudness (dB SPL) across participants for PH, PH2, SP and SP2 tasks. The difference between these two loudness levels was then compared to the difference between loudness levels of PI and PI2 vocalizations from which tracheal pressure differences could be inferred for PH, PH2, SP and SP2 tasks.

Statistical analyses.

Outliers, as determined by converting all data values to z-scores and excluding values greater than 3 standard deviations (SD) from the mean, were removed. Four outliers were removed, three from kinematic data, one from sEMG data, and none from coherence data. Coherence data values, which represent a correlation, were converted to Fisher scores prior to statistical analysis.

Averaged data were derived for each variable, task, and group. A one-way between-subject's analysis of variance (ANOVA) was performed on each dependent variable (LVINIT, LVTERM, PVCLVE, PCTRC, muscle amplitude in % MVC and peak intermuscular coherence within the 15-59 Hz bandwidth) for each task (VC, PH, PH2, SP, SP2, MEP100, MEP20, and RB). Because of the exploratory nature of this study and the first of its kind, a liberal *p* value of $p < 0.05$ was considered significant. Follow-up independent t-tests were run on the one-way between-subject's ANOVA's if the main effect of task was significant. *Bonferroni* post-hoc corrections indicated that $p < 0.008$ was needed for significance. Findings were considered to show a significant trend when $p < 0.05$. *A* within-subject's ANOVA was performed on peak coherence to compare strength of coherence across tasks for each age group. Again, because of the exploratory nature of this study and the first of its kind, a liberal *p* value of $p < 0.05$ was considered significant. Follow-up paired samples t-tests were run on the within-subject's ANOVA's if there was a significant main effect. *Bonferroni* post-hoc corrections indicated that $p < 0.002$ was needed for significance. Analyses were performed using IBM SPSS Statistics (IBM Corp, Chicago, IL).

Figures 4 - 11 show the results for lung volume and muscular events for each task. All dependent variables derived for each task are represented in one of 5 panels in each figure. For each of these figures, *Panel A* shows where participants started (LVINIT) and ended (LVTERM) a breath group for the task relative to end expiratory level (EEL). *Panel B* shows lung volume excursions in PVCLVE. *Panel C* shows percent rib cage contribution to lung volume excursions in PCTRC. *Panel D* shows the amount (amplitude) of IC and OB activation used during the task in %MVC. *Panel E* shows the strength of intermuscular coherence for the combined *beta* and low *gamma* frequency bandwidths (15-59 Hz). For the rest-breathing task, EMG was not analyzed for amplitude as it was used as an amplitude baseline measure; therefore, *Panel D* shows the strength of intermuscular coherence only. Error bars indicate 1 SD from the mean. Significant differences between the two age groups are represented by an asterisk. Statistical trends of difference between the two age groups are represented by the letter *t*.

Results

Tracheal Pressures Associated with Vocalizations. *Table 4* shows the results for estimates of tracheal pressure recordings at the level of the lips associated with conversational loudness for younger (X = 7.27 cmH_2O, SD = 1.00 cmH_2O) and older (X = 6.77 cmH_2O, SD = 1.14 H_2O) participants and perceived twice-conversational loudness for younger (X = 12.67 H_2O, SD = 1.51 H_2O) and older (X = 11.95, SD = 1.82 H_2O) participants. Loudness differences (dB SPL) between PI and PI2 were equivalent to loudness differences between PH and PH2 (*Table 5*) and; SP and SP2 *(Table 6)* thus, allowing for accurate inferences about tracheal pressures associated with these tasks.

Table 4. Estimates of tracheal pressures associated with speech at conversational loudness and twice-conversational loudness.

	[PI] Conversational Loudness		[PI] Twice-Conversational Loudness		Difference (Twice Loud – Conversational Loud)
	Sound (dBSPL) at 10cm	Pressure (cmH_2O)	Sound (dBSPL) at 10cm	Pressure (cmH_2O)	dBSPL
Young	75.93 (5.84)	7.27 (1.00)	83.37 (5.40)	12.67 (1.51)	7.44
Old	75.56 (9.98)	6.77 (1.14)	82.76 (9.32)	11.95 (1.82)	7.20

Table 5. Sound loudness differences measured between phonation at conversational loudness and at twice-conversational loudness.

	Phonation Conversational Loudness	Phonation Twice-Conversational Loudness	Difference (Twice Loud – Conversational Loud)
	(dBSPL) at 10cm	(dBSLP) at 10cm	(dBSPL) at 10cm
Young	81.72 (7.20)	87.91 (8.15)	6.19
Old	77.39 (8.63)	86.71 (8.10)	9.32

Table 6. Sound loudness differences measured between speech at conversational loudness and at twice-conversational loudness.

	Speech Conversational Loudness	Speech Twice-Conversational Loudness	Difference (Twice Loud – Conversational Loud
	(dBSPL) at 10cm	(dBSPL) at 10cm	(dBSPL) at 10cm
Young	76.57 (3.39)	84.49 (4.15)	7.92
Old	77.53 (8.79)	85.26 (8.31)	7.73

Vital Capacity. *Figure 4* shows the results for lung volume and muscular events for the VC task. A group difference was found for LVINIT ($F_{(1, 28)} = 70.02$, $p < 0.001$), LVTERM ($F_{(1, 28)} = 17.25$, $p < 0.001$), PVCLVE ($F_{(1, 28)} = 27.93$, $p < 0.001$) and PCTRC ($F_{(1, 27)} = 6.57$, $p < 0.016$). *Panel A* shows that on average, relative to EEL, younger children initiated their lung volume excursions at 1107 mLs and terminated their lung volume excursions at -461 mLs. Relative to EEL, older children initiated and terminated their lung volume excursions at 2428 mLs and -1111 mLs; respectively. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 8.37$, df = 28, $p < 0.001$) and terminated lung volume excursions at significantly lower volumes than younger participants ($t = 4.15$, df = 19.12, $p = 0.001$). *Panel B* shows that lung volume excursions were larger for older participants (112.3%VC) compared to younger participants

(74.6%VC), ($t = 5.29$, df = 28, $p < 0.001$). Note that these values are based on predicted VC values so a value of over 100% simply means that children performed better than their height-predicted values. As shown in *Panel C*, a statistical trend was found for PCTRC. Older participants produced VC maneuvers using on average, 82.0% rib cage contribution, which was lower than that observed in younger participants (PCTRC = 91.7%) ($t = 2.63$, df = 18.02, $p = 0.017$). IC muscles were activated on average between 60.8-66.6 %MVC and OB muscle amplitudes ranged between 65.1-83.9 %MVC (see *Panel D*). *Panel E* shows that on average, in the 15-59 Hz bandwidth, younger participants showed coherence of 0.31 whereas, older participants showed coherence of 0.27. This difference was not statistically significant.

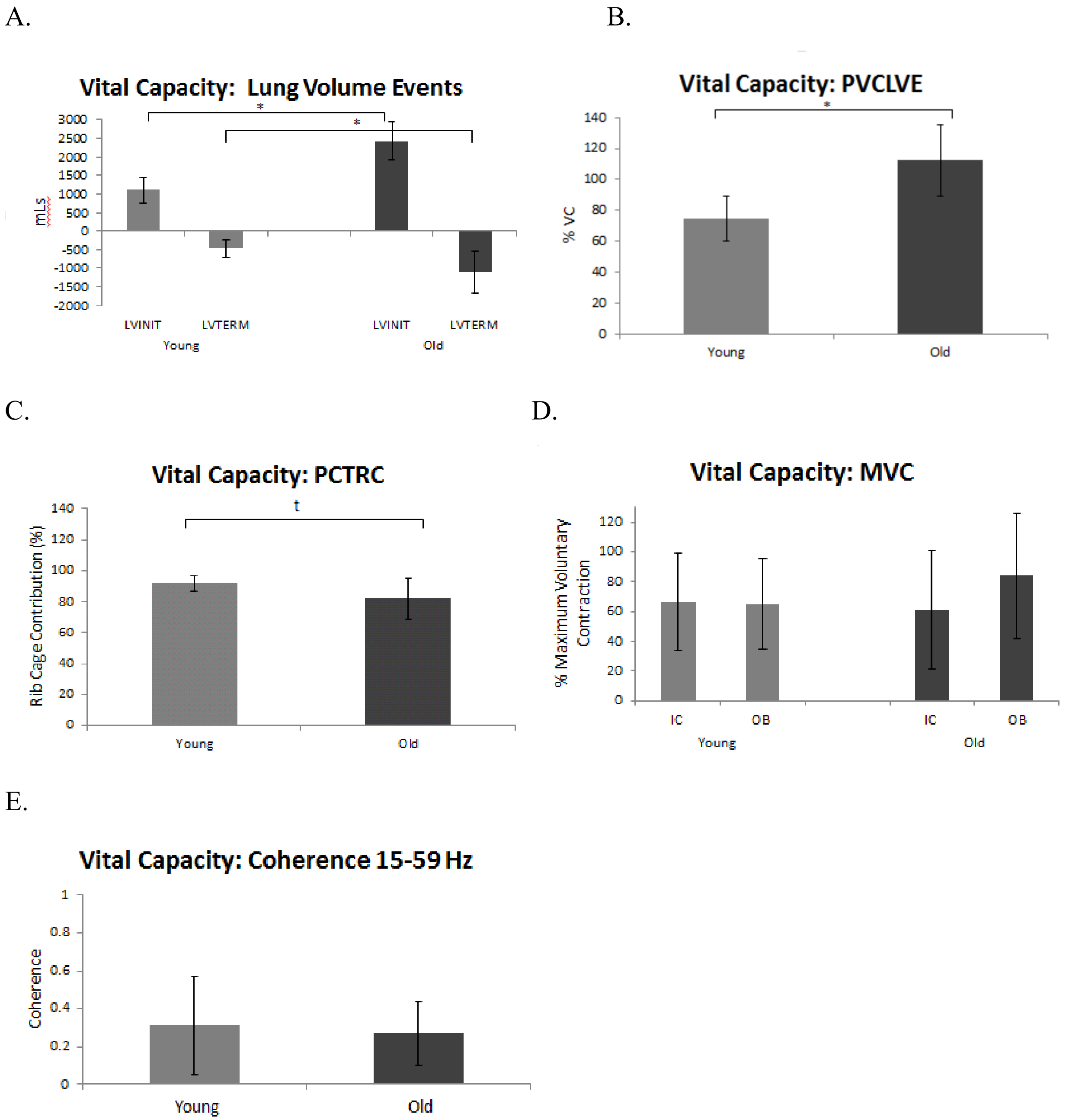


Figure 4. Lung volume and muscular events: Vital Capacity. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

Phonation. *Figure 5* shows the results for lung volume and muscular events for the PH task. A group difference was found for LVINIT ($F_{(1, 28)} = 42.22$, $p < 0.001$), LVTERM ($F_{(1, 28)} = 9.14$, $p < 0.005$), PVCLVE ($F_{(1, 28)} = 5.20$, $p < 0.030$) and PCTRC ($F_{(1, 28)} = 7.92$, $p < 0.009$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 1090 mLs and terminated their lung volume excursions at -619 mLs, relative to EEL. Older children initiated and terminated their lung volume excursions at 2332 mLs and 1036 mLs; respectively relative to EEL. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 6.50$, df = 23.76, $p < 0.001$) and terminated lung volume excursions at significantly lower volumes than younger participants ($t = 3.02$, df = 28, $p = 0.005$). As can be seen in *Panel B*, lung volume excursions showed a trend of being larger for older participants (107.1%VC) compared to younger participants (80.9%VC), ($t = 2.81$, df = 28, $p = 0.009$). A statistical trend was found for PCTRC (see *Panel C*.). Older participants produced VC manoeuvres using on average, 78.0% rib cage contribution, which was slightly lower than that observed in younger participants (PCTRC = 86.6%) ($t = 2.28$, df = 28, $p = 0.030$). IC muscles were activated on average between 28.6-37.5 %MVC and OB muscle amplitudes ranged between 33.6-34.2 %MVC (see *Panel D*). *Panel E* shows that on average, in the 15-59 Hz bandwidth, younger participants showed coherence of 0.42 whereas, older participants showed coherence of 0.57. This difference was not statistically significant.

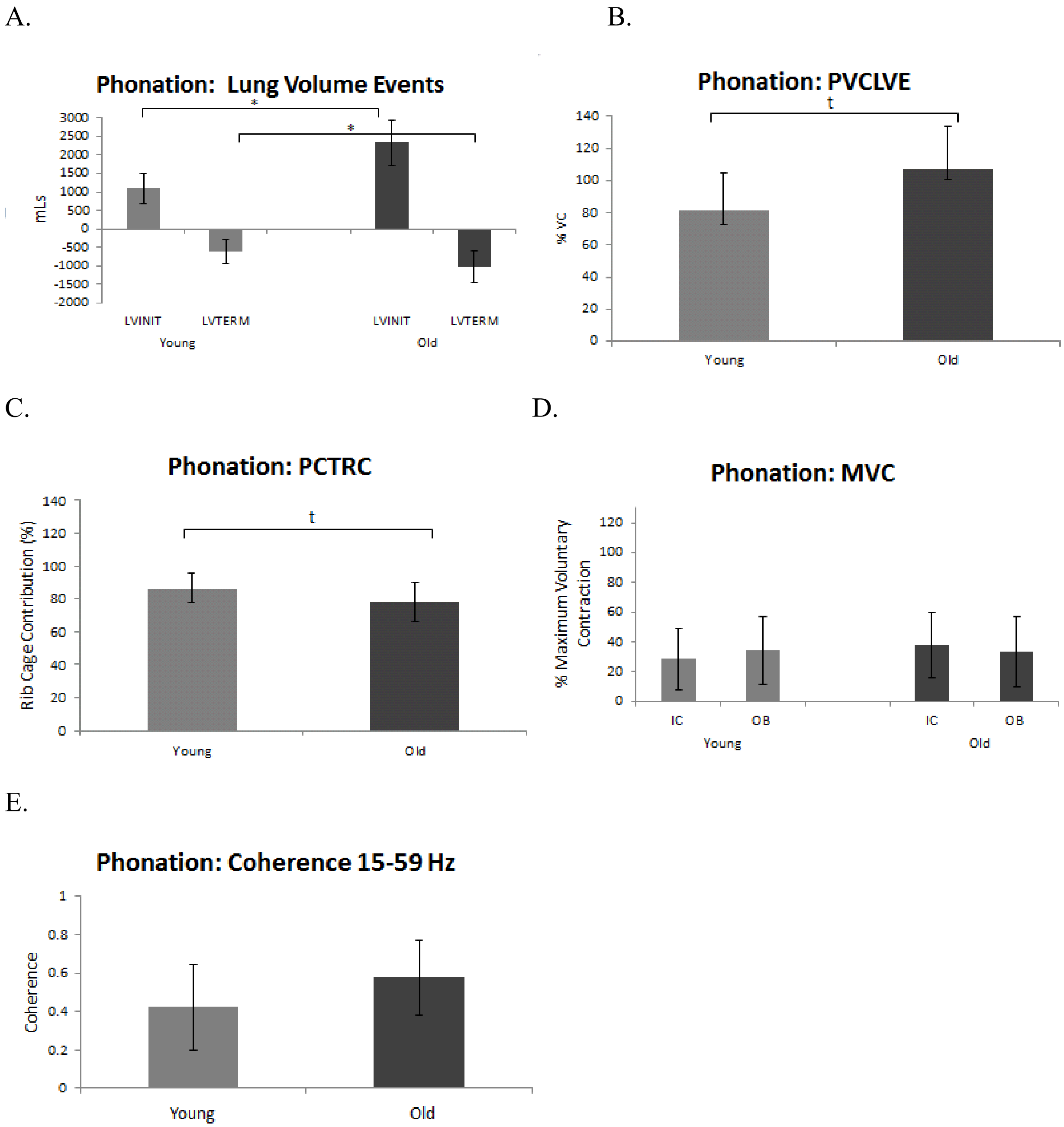


Figure 5. Lung volume and muscular events: Phonation. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

Phonation x 2. *Figure 6* shows the results for lung volume and muscular events for the PH2 task. A group difference was found for LVINIT ($F_{(1, 28)} = 37.76$, $p < 0.001$), LVTERM ($F_{(1, 28)} = 5.95$, $p < 0.021$), and PVCLVE ($F_{(1, 28)} = 6.54$, $p < 0.016$). As can be seen in *Panel A,* on average, younger children initiated their lung volume excursions at 971 mLs and terminated their lung volume excursions at -643 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 2224 mLs and -1063 mLs; respectively, relative to EEL. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 6.15$, df = 28, $p < 0.001$) and showed a trend of terminating lung volume excursions at lower volumes than younger participants ($t = 2.44$, df = 28, $p = 0.021$). *Panel B* shows that a statistical trend was found for lung volume excursions, which were larger for older participants (104.6%VC) compared to younger participants (80.5%VC), ($t = 2.56$, df = 28, $p = 0.016$). Participants in both age groups produced speech maneuvers using on average 77.6-85.3% rib cage contribution (see *Panel C*). IC muscles were activated on average between 31.8-38.4 %MVC and OB muscle amplitudes ranged between 39.4-44.9 %MVC (see *Panel D)*. *Panel E* shows that on average, in the 15-59 Hz bandwidth, younger participants showed coherence of 0.40 whereas, older participants showed coherence of 0.53. This difference was not statistically significant.

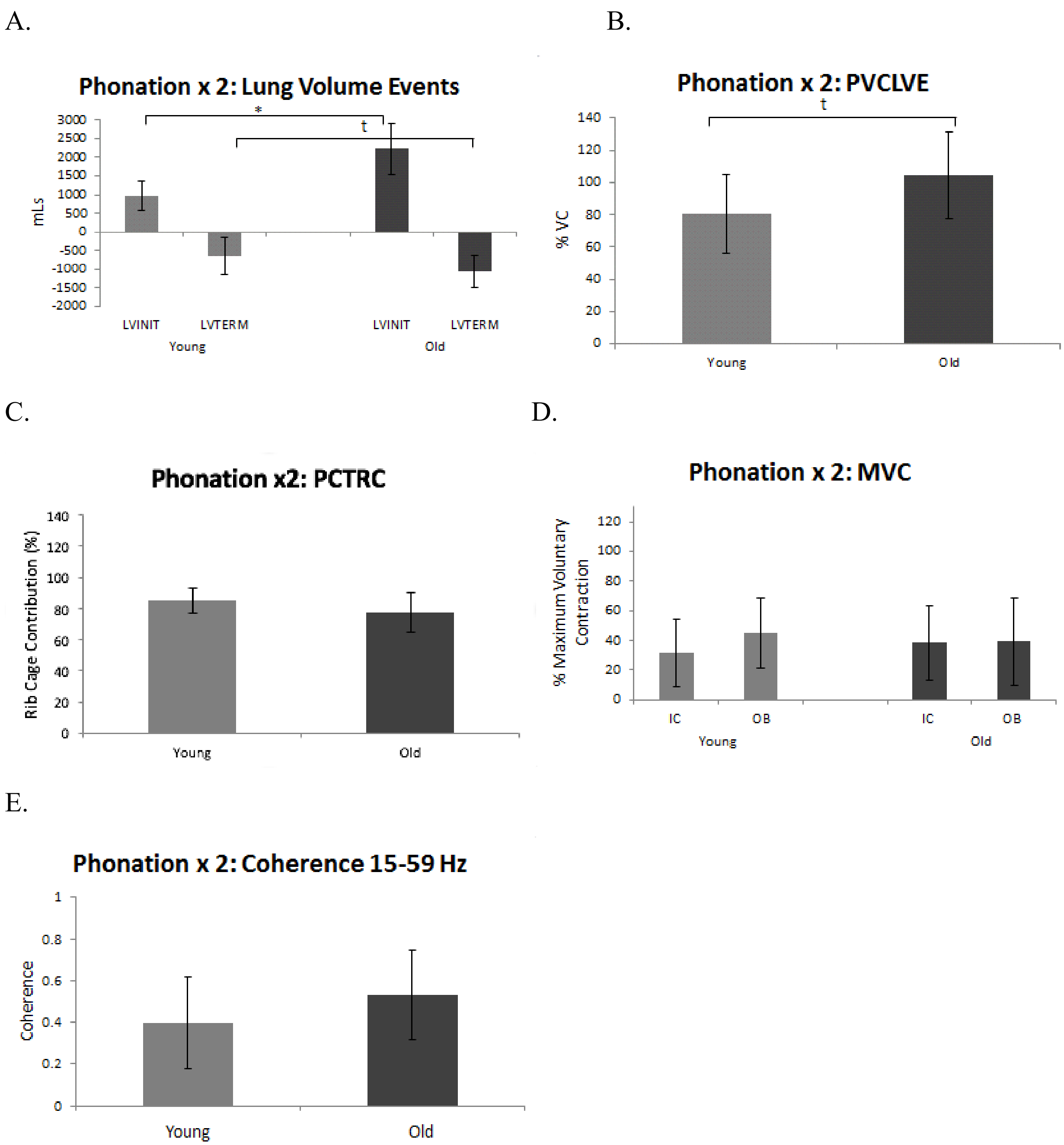


Figure 6. Lung volume and muscular events: Phonation x 2. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

Speech. *Figure 7* shows the results for lung volume and muscular events for the SP task. A group difference was found for LVINIT ($F_{(1, 28)} = 16.47$, $p < 0.001$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 275 mLs and terminated their lung volume excursions at -77 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 397 mLs and -107 mL; respectively, relative to EEL. A follow-up independent *t*-test showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 4.06$, df = 28, $p < 0.001$). All participants terminated lung volume excursions at similar lung volumes. *Panel B* shows that lung volume excursions for all participants were in the same average range, 16.0-16.8%VC. Participants in both age groups produced speech maneuvers using on average 70.5-73.9% rib cage contribution (see *Panel C*). A group difference was found for IC ($F_{(1, 28)} = 5.02$, $p < 0.033$) and OB ($F_{(1, 26)} = 7.57$, $p < 0.011$) muscle amplitude in terms of %MVC, which showed a statistical trend that older children activate their muscles at lower %MVC than younger children ($t = 2.24$, df = 28, $p = 0.033$) and ($t = 2.89$, df = 20.51, $p = 0.009$); respectively. Older and younger children's IC muscles were activated on average, at 13.3 %MVC and 22.2% MVC, respectively. Older and younger children's OB muscles were activated on average, at 12.0 %MVC and 20.7% MVC, respectively (see *Panel D*). A group difference was found for coherence ($F_{(1, 27)} = 6.23$, $p < 0.019$). *Panel E* shows that on average, younger participants showed coherence of 0.58 whereas, older participants showed coherence of 0.76. Older participants exhibited a statistical trend of higher intermuscular coherence in the 15-59 Hz bandwidth ($t = -2.50$, df = 27, $p = 0.019$) than their younger counterparts.

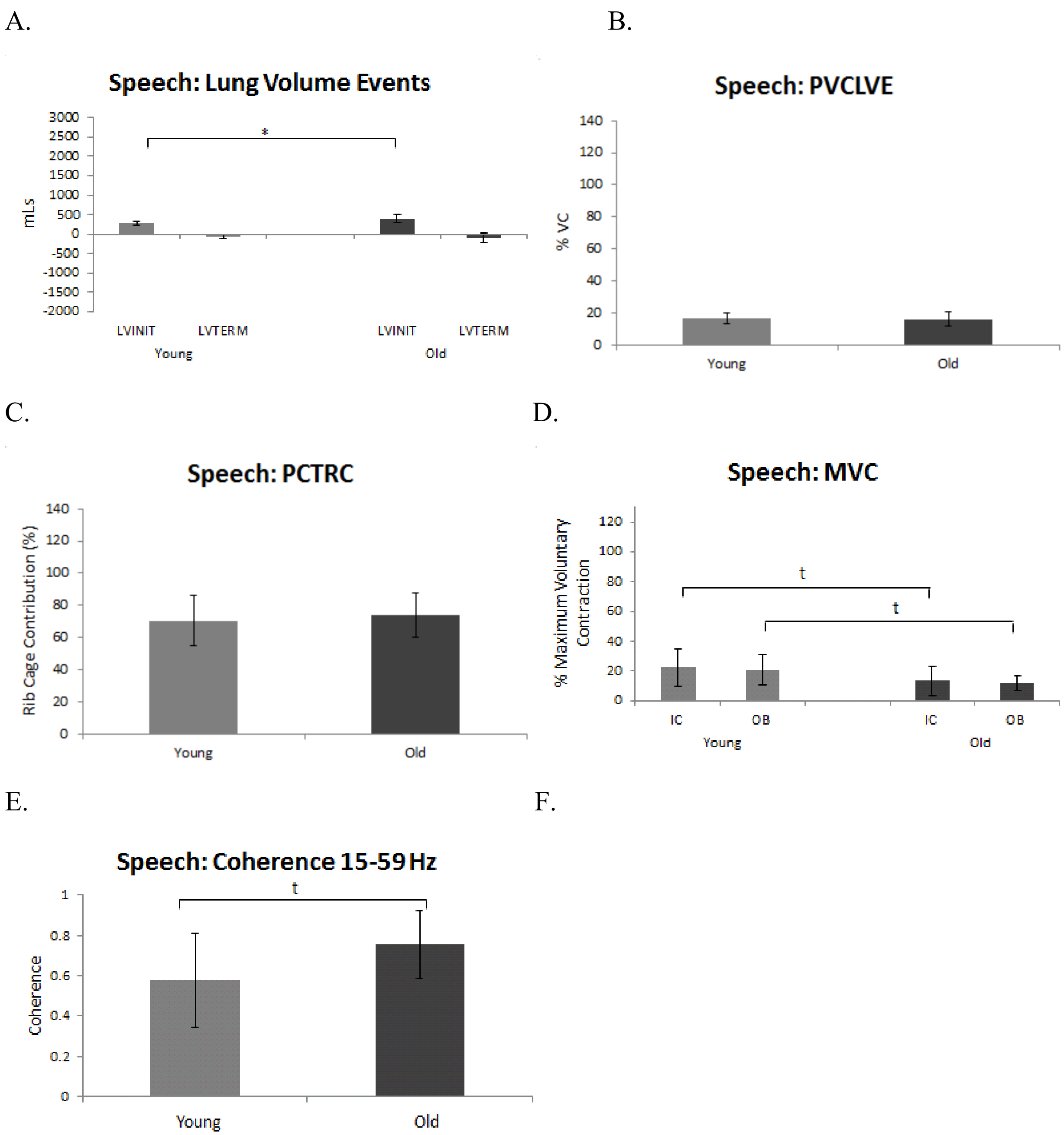


Figure 7. Lung volume and muscular events: Speech. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter t ($p < 0.05$). Error bars indicate 1 SD from the mean.

Speech x 2. *Figure 8* shows the results for lung volume and muscular events for the SP2 task. A group difference was found for LVINIT ($F_{(1, 28)} = 36.13$, $p < 0.001$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 323 mLs and terminated their lung volume excursions at -101 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 632 mLs and -80 mLs; respectively, relative to EEL. A follow-up independent *t*-test showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 6.01$, df = 28, $p < 0.001$). All participants terminated lung volume excursions at similar lung volumes. Shown in *Panel B,* lung volume excursions for participants in both age groups were in the same average range, 20.3-22.8%VC. Participants in both age groups produced speech maneuvers using on average 71.4-77.2% rib cage contribution (see *Panel C)*. A group difference was found for IC ($F_{(1, 28)} = 12.64$, $p < 0.001$) and OB ($F_{(1, 27)} = 11.24$, $p < 0.002$) muscle activation amplitude in %MVC, which showed that older children activate their IC and OB muscles at significantly lower %MVC than younger children ($t = 3.557$, df = 28, $p = 0.001$) and ($t = 3.35$, df = 27, $p = 0.002$) respectively. Older and younger children's IC muscles were activated on average, at 14.7 %MVC and 28.1% MVC; respectively and OB muscles were activated on average, at 14.6 %MVC and 29.7 %MVC; respectively (see *Panel D*). A group difference was found for coherence ($F_{(1, 25)} = 5.75$, $p < 0.024$). Older participants exhibited a statistical trend of higher intermuscular coherence in the 15-59 Hz bandwidth ($t = 2.40$, df = 25, $p = 0.024$) than their younger counterparts. Specifically, *Panel E* shows that on average, younger participants showed coherence of 0.49 whereas, older participants showed coherence of 0.70.

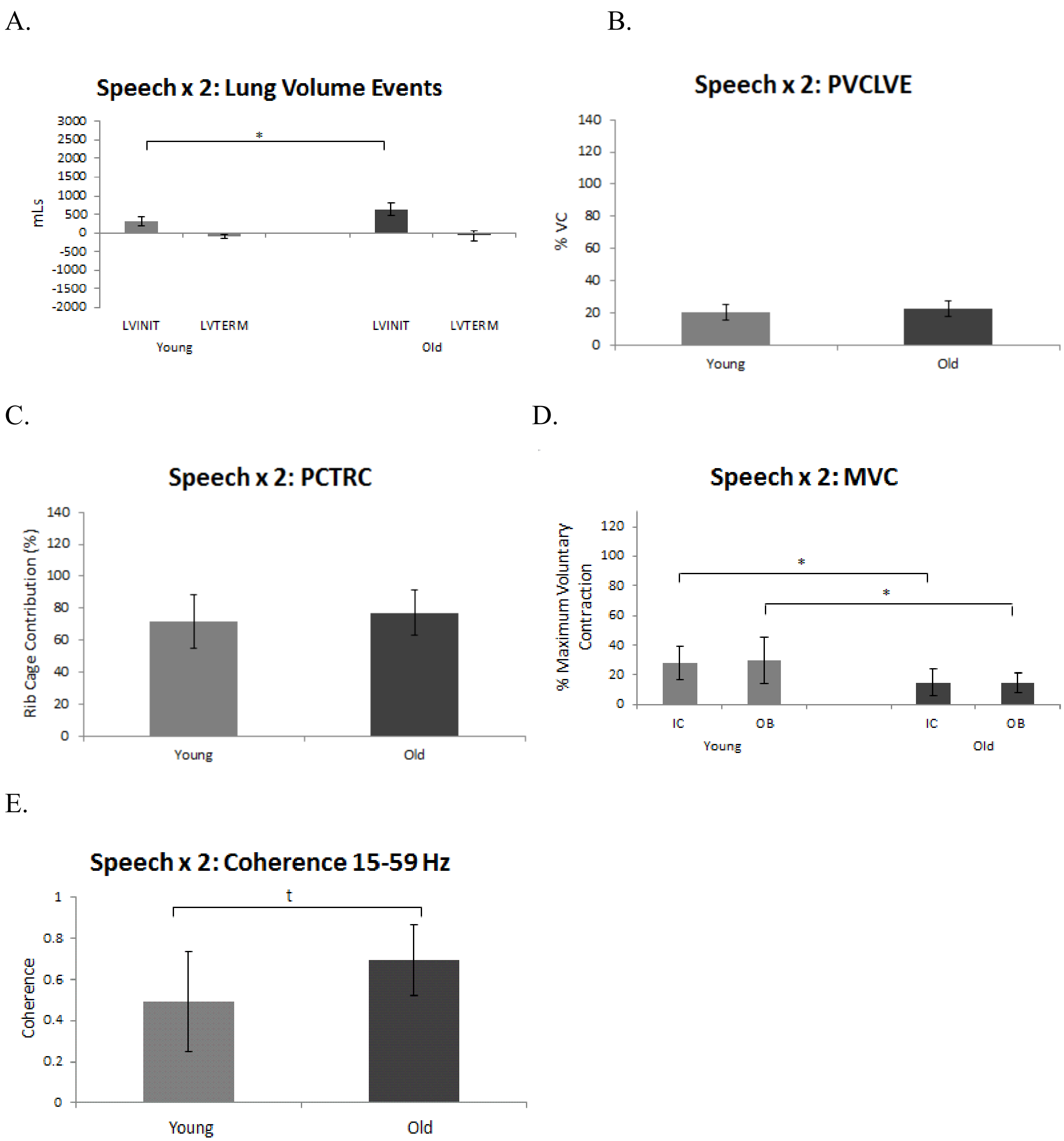


Figure 8. Lung volume and muscular events: Speech x 2. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

Rest Breathing. *Figure 9* shows the results for lung volume and muscular events for the rest breathing task. A group difference was found for LVINIT ($F_{(1, 28)} = 82.44$, $p < 0.001$) and PVCLVE ($F_{(1, 28)} = 5.70$, $p < 0.024$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 242 mLs and terminated their lung volume excursions at -4 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 395 mLs and 14 mLs; respectively, relative to EEL. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 9.08$, df = 28, $p < 0.001$) and terminated lung volume excursions at similar lung volumes. As can be seen in *Panel B,* a statistical trend was found for lung volume excursions, which were larger for older participants (12.1%VC) compared to younger participants (11.3%VC), ($t = 2.39$, df = 23.38, $p = 0.025$). *Panel C* shows that all participants produced rest breathing maneuvers using on average, 65.8-69.0% rib cage contribution. On average, in the 15-59 Hz bandwidth, younger participants showed coherence of 0.74 whereas, older participants showed coherence 0.69 (see *Panel D*). This difference what not statistically significant.

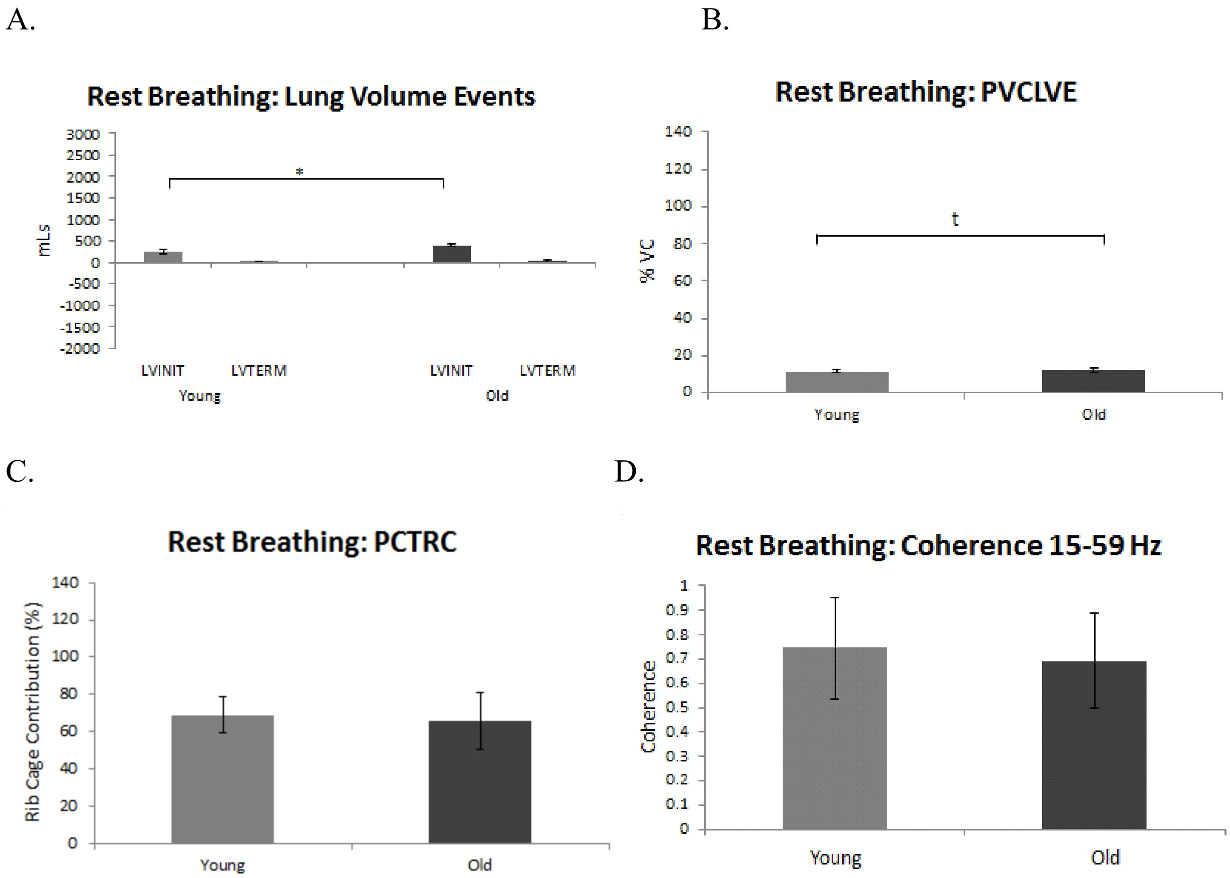


Figure 9. Lung volume and muscular events: Rest Breathing. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**, respectively. Peak coherence for combined beta and low gamma frequency bandwidths (15-59 Hz) are shown in **D**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

100% MEP. *Table 7* shows the results for the average pressures generated by younger (X = 53.95 cmH_2O, SD = 17.95 cmH_2O) and older (X = 83.72 cmH_2O, SD = 16.68 cmH_2O) participants at 100% MEP.

Table 7. Pressures generated by participants at 100% MEP and 20% MEP.

	100% MEP Pressure (cmH_2O)	20% MEP Pressure (cmH_2O)
Young	53.95 (17.92)	32.99 (4.31)
Old	83.72 (16.68)	40.57 (5.20)

Figure 10 shows the results for lung volume and muscular events for the 100% MEP task. A group difference was found for LVINIT ($F_{(1, 23)} = 42.82$, $p < 0.001$), LVTERM ($F_{(1, 23)} = 49.93$, $p < 0.001$), and PVCLVE ($F_{(1, 23)} = 4.62$, $p < 0.042$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 903 mLs and terminated their lung volume excursions at 249 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 2024 mLs and 1353 mLs; respectively, relative to EEL. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants ($t = 6.54$, df = 23, $p < 0.001$) and terminated lung volume excursions at higher volumes than younger participants ($t = 7.07$, df = 23, $p < 0.001$). *Panel* B shows that a statistical trend was found for lung volume excursions, which were slightly smaller for older participants (21.2%VC), than for younger participants, (30.6%VC) (t =2.15, df = 23, $p = 0.042$). Participants in both age groups produced 100% MEP maneuvers using on average 91.0-103.5% rib cage contribution (see *Panel C*). IC muscles were activated on average between 44.0-48.5 %MVC and OB muscle amplitudes ranged between 48.1-58.6 %MVC (see *Panel D*). *Panel E* shows that on average, in the 15-59 Hz bandwidth, younger and older participants showed similar coherence values of 0.37 and 0.36; respectively.

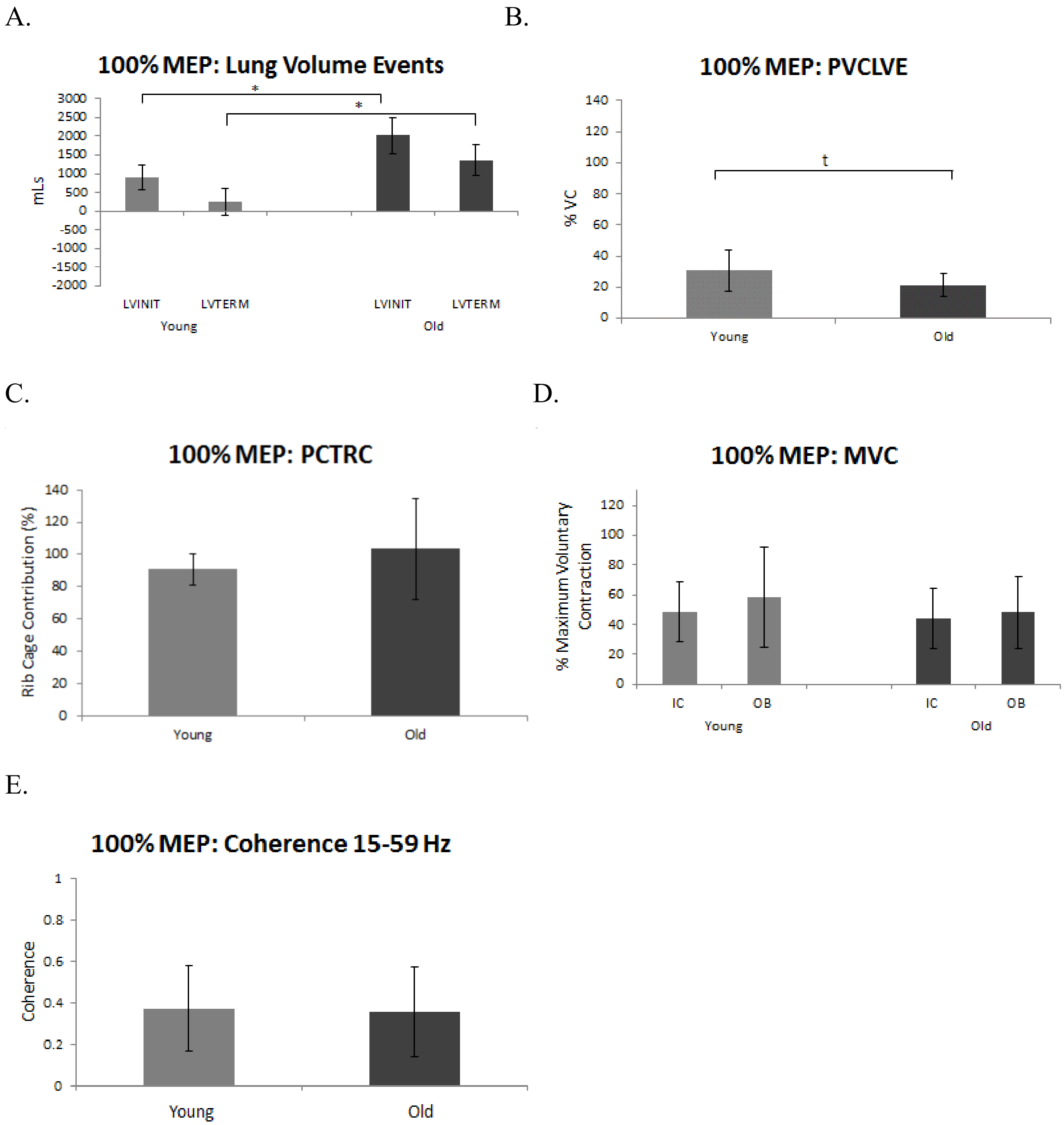


Figure 10. Lung volume and muscular events: 100% MEP. Lung volume initiation and termination (LVINIT, LVTERM) (**A**.) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

20% MEP. *Table 7* shows the results for the average pressures generated by younger (X = 32.99 cmH_2O, SD = 4.31 cmH_2O) and older (X = 40.57 cmH_2O, SD = 5.20 cmH_2O) participants at 20% MEP. *Figure 11* shows the results for lung volume and muscular events for the 20% MEP task. A group difference was found for LVINIT ($F_{(1, 23)} = 54.90$, $p < 0.001$), LVTERM ($F_{(1, 23)} = 4.31$, $p < 0.049$), PVCLVE ($F_{(1, 23)} = 13.76$, $p < 0.001$), and PCTRC ($F_{(1, 22)} = 6.28$, $p < 0.020$). *Panel A* shows that on average, younger children initiated their lung volume excursions at 972 mLs and terminated their lung volume excursions at -292 mLs relative to EEL. Older children initiated and terminated their lung volume excursions at 2250 mLs and -812 mLs; respectively, relative to EEL. Follow-up independent *t*-tests showed that older participants initiated lung volume excursions at significantly higher volumes than younger participants (t = 7.56, df = 19.70, $p < 0.001$) and showed a trend of terminating lung volume excursions at lower lung volumes than younger participants (t = 2.075, df = 23, p = 0.049). As can be seen in *Panel B,* lung volume excursions were larger for older participants (96.6%VC), than for younger participants, (58.8%VC) (t =3.71, df = 23, p = 0.001). A statistical trend was found for PCTRC. Older participants produced VC maneuvers using on average, 79.3% rib cage contribution, which was slightly lower than that observed in younger participants (PCTRC = 86.1%) (t = 2.51, df = 22, p = 0.020) (see *Panel C)*. IC muscles were activated between 56.4-62.1 %MVC and OB muscle amplitudes ranged between 58.7-70.9 %MVC (see *Panel D)*. *Panel E* shows that on average, in the 15-59 Hz bandwidth, younger participants showed coherence showed similar coherence values of 0.37 and 0.34; respectively.

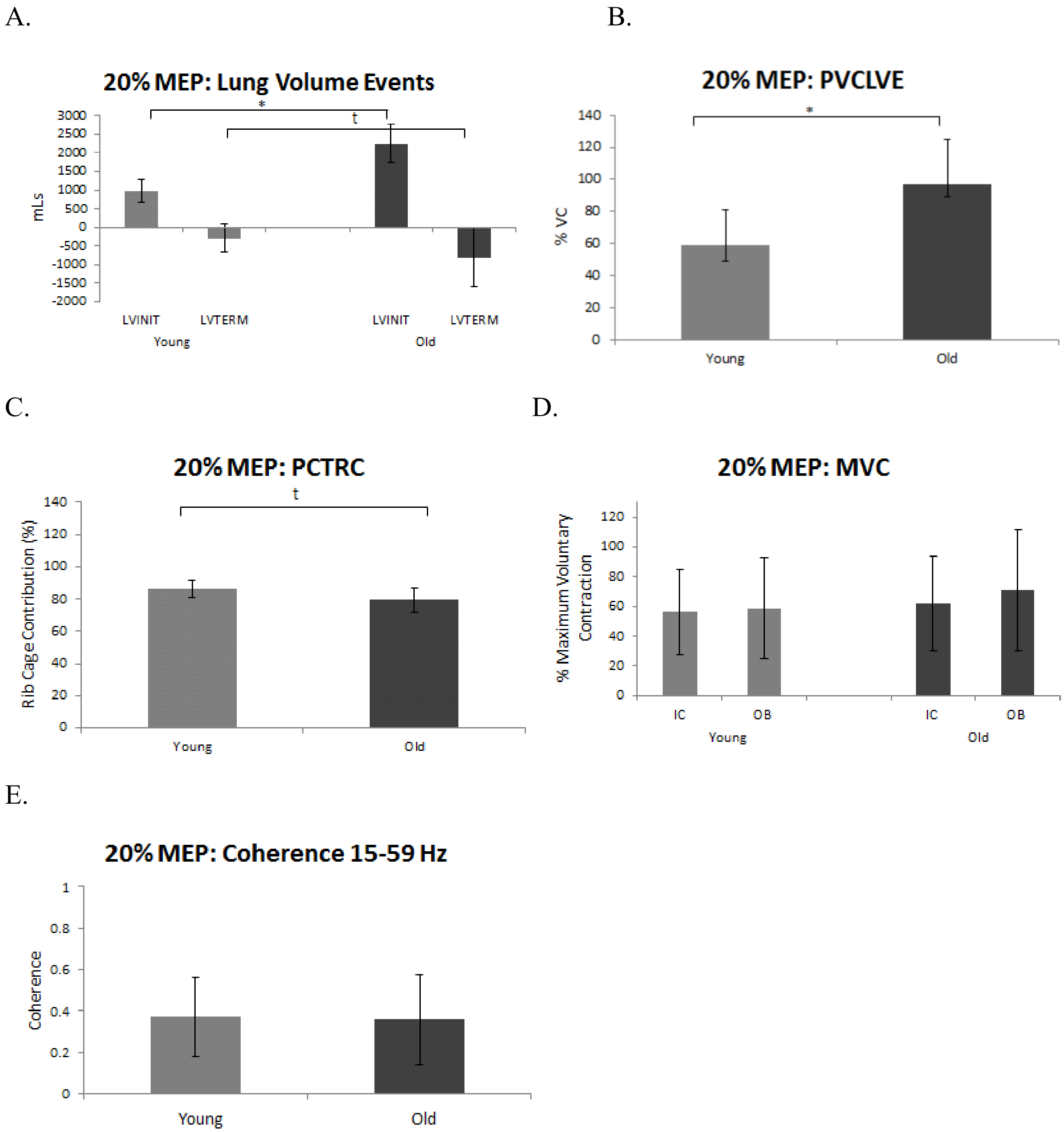


Figure 11. Lung volume and muscular events: 20% MEP. Lung volume initiation and termination (LVINIT, LVTERM) (**A.**) are displayed in mLs relative to end expiratory level (EEL). Lung volume excursions in percent predicted VC (PVCLVE) and percent rib cage contribution to lung volume excursion (PCTRC) are shown in **B** and **C**; respectively. The amount of IC and OB muscular activity in percent maximum voluntary contraction (MVC) is shown in **D**. Peak coherence for the combined beta and low gamma frequency bandwidths (15-59 Hz) is shown in **E**. Significant differences between the two age groups are represented by an asterisk ($p < 0.008$). Statistical trends of difference between the two age groups are represented by the letter *t* ($p < 0.05$). Error bars indicate 1 SD from the mean.

Overall coherence: *Figure 12* shows overall coherence results from the one-way between-subject's ANOVA's with appropriate post hoc tests. Older participants have visibly greater coherence than younger participants for tasks involving phonation (i.e., vocal fold movement), including SP, SP2, PH and PH2, and the two groups have similar coherence for breathing tasks, including VC, MEP20, MEP100 and RB. Red circles indicate statistical trends of difference between the two age groups for the SP and SP2 tasks ($p < 0.008$).

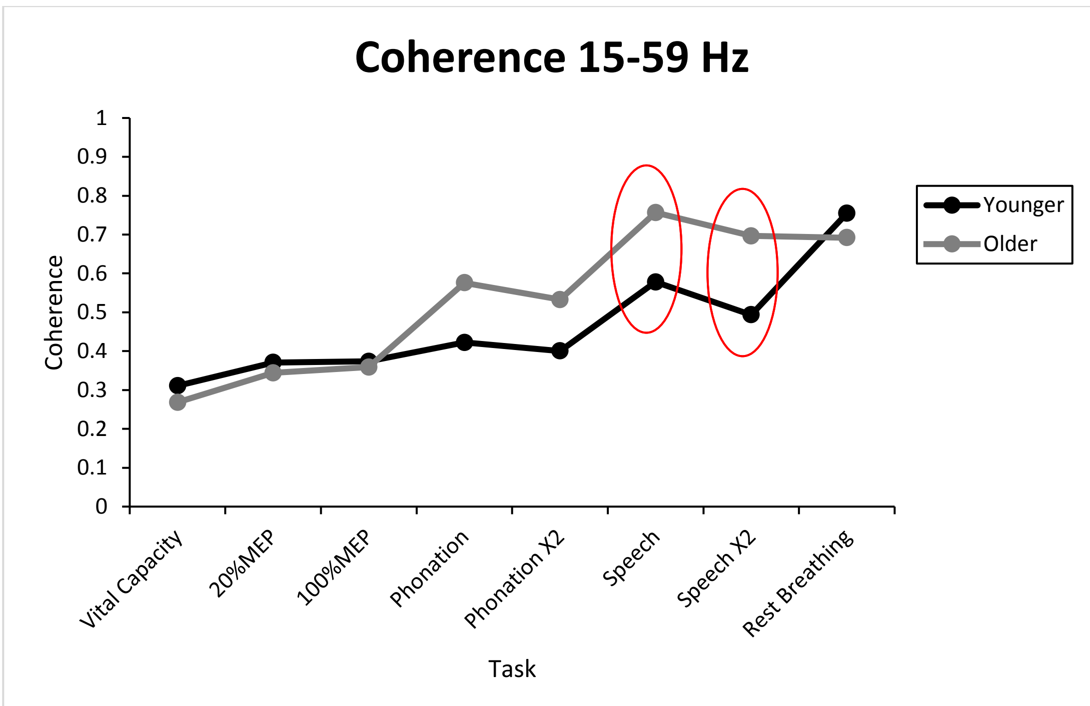


Figure 12. Coherence by task within each group in the beta and low gamma frequency band (15-59 Hz). Tasks completed and strength of coherence are represented on the *x* and *y* axes; respectively. Statistical trends of difference between the two age groups are represented by the red circles on select tasks.

Task specific coherence within group: Younger Children. *Figure 13* shows coherence difference by task within the younger developmental age group. Statistically significant differences were found between the following tasks ($p < 0.002$, *Bonferroni* correction value), see *Table 8*.

Table 8. Statistically significant difference of coherence between tasks within the younger age group. *t* values and probability values for within subjects follow up paired samples t-tests.

Task 1	Task 2	*t* value	Degrees of Freedom	Significance (*p*)
VC	SP	7.23	8	<0.001
VC	SP2	5.34	8	0.001
RB	MEP20	5.82	9	<0.001
RB	MEP100	5.23	10	<0.001
RB	PH	4.41	12	0.001
RB	PH2	5.11	12	<0.001
MEP100	SP	4.87	11	<0.001
PH2	SP	5.13	12	<0.001

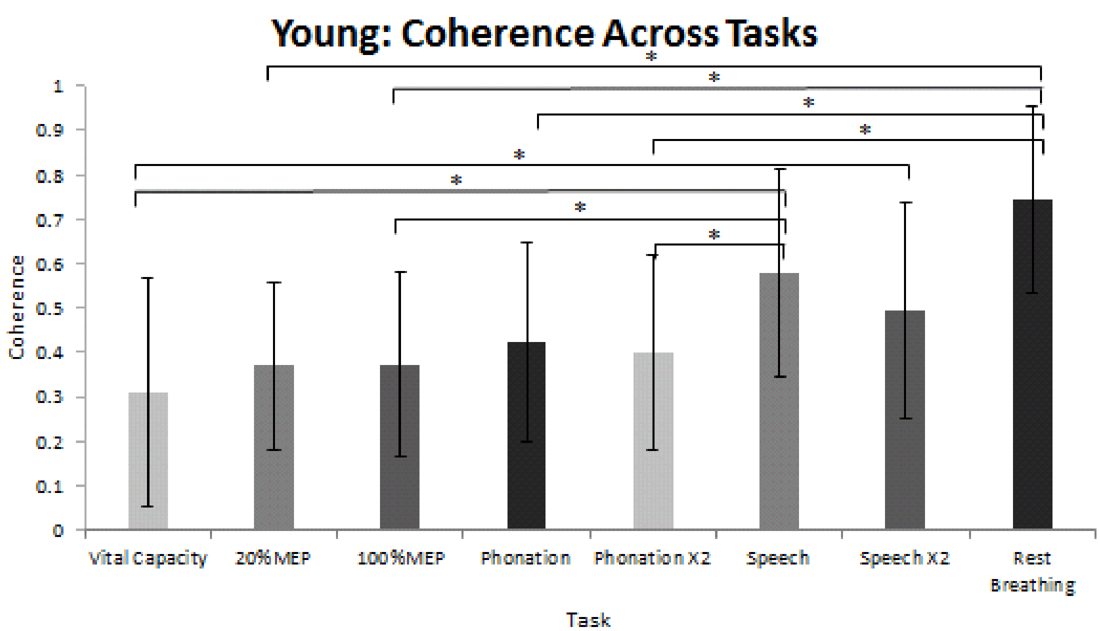


Figure 13. Coherence by task for younger children in the beta and low gamma frequency band (15-59 Hz). Tasks completed and strength of coherence are represented on the *x* and *y* axes; respectively. Significant differences between any two given tasks are represented by asterisks.

Task specific coherence within group: Older Children. *Figure 14* shows coherence difference by task within the older developmental age group. Statistically significant differences were found between the following tasks ($p < 0.002$, *Bonferroni* correction value), see *Table 9*.

Table 9. Statistically significant difference of coherence between tasks within the older age group. *t* values and probability values for within subjects follow up paired samples t-tests.

Task 1	**Task 2**	***t* value**	**Degrees of Freedom**	**Significance (*p*)**
VC	RB	4.51	13	0.001
VC	PH	6.04	13	<0.001
VC	PH2	4.22	13	0.001
VC	SP	7.78	13	<0.001
VC	SP2	6.17	13	<0.001
PH	SP	4.52	14	<0.001
PH	MEP100	5.27	10	<0.001
PH2	SP	4.58	14	<0.001
PH2	MEP100	4.72	10	0.001
MEP100	SP	8.97	10	<0.001
MEP100	SP2	6.74	10	<0.001
MEP20	SP	7.93	7	<0.001
MEP20	SP2	7.17	7	<0.001

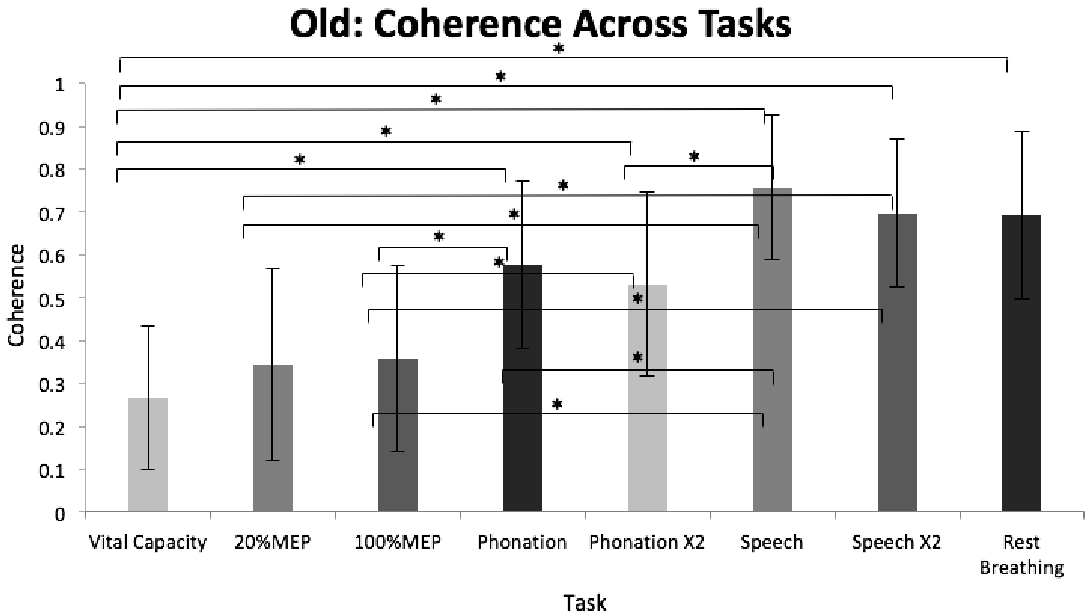


Figure 14. Coherence by task for older children in the beta and low gamma frequency band (15-59 Hz). Tasks completed and strength of coherence are represented on the *x* and *y* axes; respectively. Significant differences between any two given tasks are represented by asterisks.

Discussion

This study aimed to enhance our understanding of developmental changes in intermuscular coherence of the chest wall for non-speech and speech tasks. Younger and older children performed a series of tasks designed to manipulate lung volumes and alveolar pressures. The main findings were: (1) Whereas breathing patterns for speech were similar between the two groups of children, those for tasks involving larger alveolar pressure requirements or greater lung volume excursions differed between the age groups. (2) Muscle activation amplitudes differed only between the two age groups for tasks involving speech. (3) Similarly, intermuscular coherence, differed only on tasks involving speech. (4) Within groups, intermuscular coherence for task specificity was more precisely developed in the older group compared to the younger group of children. Younger children showed a lower amount of muscle coordination, whereas older children exhibited greater muscle coordination patterns.

Lung Volume Events

Collectively taken, participants in both age groups exhibited generally similar respiratory patterns for speech breathing to one another, although previous studies (Boliek, et al., 2009; Hoit et al., 1990; Stathopoulos and Sapienza, 1993 &1997) have noted speech breathing differences between younger and older children in terms of PVCLVE and PCTRC. Discrepancies between the present data and previous speech breathing literature may arise from the nature of speech breathing tasks. Sentence repetition provides a constrained format of speech breathing as compared to conversational speaking or continuous speech produced when reading a passage used in the previous studies cited above. Overall, breathing patterns for speech tasks differed from those for non-speech tasks. Differences between the two groups primarily occurred on non-speech tasks requiring the greatest lung volume excursion (VC, PH, & PH2) and tasks requiring the greatest maximum expiratory pressures (MEP20 & MEP100). Most noteworthy of differences, were those of the MEP100 task.

We hypothesized that younger and older children would exhibit different absolute lung volume initiations. Older children were able to initiate at (absolute) higher lung volumes for all tasks, and terminate at (absolute) lower lung volumes for non-speech tasks, save for the MEP100 task. Developmental differences here are expected, and in line with findings from Boliek et al., 2009, as physical growth associated with age conditions the magnitude of the events observed (Hoit et al., 1990; Stathopoulos and Sapienza, 1993). We hypothesized that older children would have relatively stable lung volume terminations and excursions whereas younger children would exhibit greater variability. Children across both age groups underwent similar variability in lung volume terminations and excursions. Due to the constraints placed on speech breathing by utilizing a sentence repetition task, and resulting similar lung volume events, this result is not unexpected. Older children initiated speech at higher lung volumes, allowing for greater excursions without lower terminations. Additionally, older participants were able to use considerably larger percentages of their predicted VC when expelling air from the lungs for all non-speech tasks, save for the MEP100 task. This is likely due to developmental increases in chest wall stiffness (lower compliance) and its effect on recoil pressures of the chest wall (Hixon et al., 2014; Hoit et al., 1990). Younger children, who exhibit greater compliance and resulting lower static recoil pressures, must move their rib cage and abdomen much more than older children in order to accomplish the same lung volume displacement. Stathopoulos and Sapienza (1993) provide a geometrical explanation for this. If the thorax is idealized as a uniformly contracting sphere, then the volume of the sphere mathematically varies as a cube of its diameter. Thus, an adult whose rest diameter is twice that of a child would produce eight times as much air volume as a child with the same absolute change in rib cage diameter. In the present study, older children were able to utilize a larger percentage of the air within their lungs for each task because increased stiffness and diameter of the chest wall creates a more efficient system for lung volume excursion.

In breathing for speech, older children are expected to utilize a stable contribution of the rib cage to lung volume excursion (approximately 80%) (Hoit et al., 1990; Stathopoulos and Sapienza, 1993 & 1997). We hypothesized that younger children would present variable contributions of the rib cage and abdomen across tasks relative to their more stable older counterparts. In the present study, both age groups of children used similar, stable, rib cage contributions for speech tasks and non-speech tasks involving lung volume excursions in the midrange of VC, which contrasts previous reports. Additionally, older children were able to effectively use greater abdomen contribution at lower lung volumes (i.e., in tasks involving maximal lung volume excursion) than younger children. One explanation for this may be provided by Boliek et al. (2009). When breath groups terminate at volumes smaller than EEL, and approximate the lowest portion of the functional range, as in tasks requiring maximum lung volume excursion, then the abdomen is biomechanically advantaged for providing expiratory drive (i.e., the abdomen can continue inward displacement against soft abdominal contents in contrast to limits placed on inward articulation of rib joints). Thus, a relatively larger abdominal contribution would be observed. Children in the younger age group are still undergoing changes in chest wall compliance, static lung compliance, airway resistance and size (Clair-Auger et al., 2015) and continue to explore a variety of rib cage and abdomen contributions against a changing physical and linguistic environment (Boliek et al., 2009). Whereas greater rib cage contribution, of approximately 80%, to speech has been documented to be biomechanically preferred in adult-like speech (Hoit et al., 1990; Stathopoulos and Sapienza, 1997), younger children in the present study may have been overshooting the use of the rib cage during excursions in this period of refinement.

The MEP100 task revealed that at maximum expiratory pressures, older children initiated and terminated lung volume excursions at (absolute) higher lung volumes while undergoing, on average, a similar (absolute) excursion to younger children. Older children appear to have been taking advantage of the inherent recoil characteristics of the lungs (Hixon et al., 1973). Unlike the other tasks, both older and younger children terminated excursions well above EEL due to the considerably greater pressure required to expel air from the lungs. Different from all other tasks involved, younger children utilized a larger percentage of their predicted VC for lung volume excursion in this task. This is in line with previous findings that indicate that pressure generation capability of the breathing musculature increases with age (Hoit et al., 1990) and the hypothesis that younger children are less efficient at managing their airway flows and thus compensate for larger laryngeal flow by using a larger percentage of their VC (Stathopoulos and Sapienza, 1993). Because of their smaller vital capacity, and increased lung compliance, younger children use a greater proportion of their vital capacity to generate increased pressures (Solomon and Charron, 1998). Lower compliance and a stiffer chest wall in older children, allows them to be more biomechanically efficient when exerting pressure against resistance (Stathopoulos and Sapienza, 1997).

Muscle MVC

We know that the recruitment of muscular effort is required to sustain the targeted tracheal pressures for each task with the exception of VC and rest breathing (Hixon and Weismer, 1995). As expected, overall tasks requiring higher alveolar pressures were accomplished with the recruitment of greater chest wall muscular activity (Clair-Auger et al., 2015; Hixon and Weismer, 1995; McFarland and Smith, 1989; Watson et al., 1989). Our protocol successfully validated that increased loudness (in dBSPL) was indeed related to greater tracheal pressures (see *Table 4*). Similarly, we found that tasks requiring greater lung volume excursion were also accomplished with the recruitment of greater relative chest wall muscular activity (i.e., %MVC). We hypothesized that younger children would exhibit greater muscle activation amplitudes compared to older children. Interestingly the only developmental difference related to %MVC was found in the speech tasks (SP and SP2). Younger children recruited more intercostal and oblique muscular effort than did their older counterparts. This was likely necessary due to a more compliant chest wall than that of their older counterparts (Clair-Auger et al., 2015; Tang and Stathopoulos, 1993). Due to increased compliance and lower static recoil pressures, younger children must either start at a higher lung volume or use more expiratory muscle force in order to generate the same pressures as older children (Stathopoulos and Sapienza, 1997). For speech at conversational and twice-conversational loudness, younger children modulated pressure increases with the use of greater muscular effort.

Intermuscular Coherence

We hypothesized that a developmental difference would exist for intermuscular coherence of tasks varying in lung volume and/or alveolar pressure targets dependent on features of skill and strength. Overall, a developmental difference for intermuscular coherence was found between children above and below the age at which speech breathing has been determined to be adult-like in nature (Hoit et al., 1990). A trending divergence of coherence values between younger and older children occurred only on tasks involving the production of speech. It has been found that intermuscular coherence is at least, in part, a measurement of corticospinal tract innervation of peripheral muscles (Hansen et al., 2005; Norton & Gorassini, 2006, Fisher et al., 2012). General consensus is that intermuscular coherence is a measurement of muscle coordination between disparate muscles (Boonstra, 2013). Interpretation of previous findings provides valuable support that increased intermuscular coherence could represent neuromuscular drive associated with increased muscle coordination, whereas decreased intermuscular coherence could represent neuromuscular drive associated with a decreased amount of muscle coordination in the context of mature adult models. In the present study, older participants exhibited higher peak coherence patterns for speech breathing tasks. Interestingly, both groups of children displayed similar, higher peak coherence, for rest breathing and similar, lower peak coherence for non-speech breathing tasks. These findings may indicate that speech breathing tasks in the present study are still undergoing a period of refinement in younger children.

Tasks in the present study were designed to manipulate the amount of air expelled from the lungs (lung volume excursion) and the amount of pressure required to expel this air (alveolar pressure). These manipulations were designed to vary the force, or strength level required by children. However, tasks chosen also varied on level of skill in terms of routineness or over-learning. More specifically, speech tasks, though complex in terms of articulatory and linguistic components of the speech mechanism, are over-learned and routine in older children and adult speakers. Similarly, rest breathing is an over-learned and routine activity, in both older and younger children. Taken together, these tasks (SP, SP2 and RB) probably represent a degree of automaticity. In comparison, non-speech tasks designed to portray the maximal amount of lung volume excursion or alveolar pressure, though less complex in the linguistic and articulatory context, are somewhat novel at any age. Taken together, these tasks (VC, PH, PH2, MEP100, MEP20) could represent a generally novel and non-learned skill. Thus, the tasks within the present study can naturally be separated into two levels of skill in an adult-like speech model: over-learned and novel. Further classified, over-learned tasks occurred in the midrange of VC, and novel tasks, save for MEP100, occurred over the broad range of VC. Developmental differences in intermuscular coherence values for these two task types are evident across and within the two developmental age groups examined.

Speech Breathing

Intermuscular coherence was higher for all participants in the over-learned tasks and lower for all participants in the novel tasks. Whereas lung volume events for the novel tasks showed the greatest developmental differences in terms of the amount of air utilized per breath group and the rib cage and abdominal contribution, these tasks produced low coherence values for all participants. These findings are in line with Semmler et al. (2004) who found that high complexity skilled tasks resulted in a reduced level of motor unit coherence, possibly due to oscillatory drive occurring though a greater number of independent inputs. Perez et al. (2012) also showed increasing force levels, apparent in the novel tasks utilized here, caused a reduction in the 15-30 Hz coherence bandwidth. Stepp et al. (2011) showed that intermuscular coherence values were much lower for complex speaking tasks (divided attention) relative to typical speech. Interestingly, speech tasks, which showed similar lung volume and muscular events between our two age groups, resulted in coherence patterns that appeared to be sensitive to age. Younger children may have experienced greater difficulty completing speech tasks than older participants. The present findings indicate that whereas children of different developmental ages use similar muscle coordination patterns to control novel tasks, a developmental difference is evident for tasks requiring speech production.

One model that can be used to interpret these data is the Direction into Velocities of Articulators (DIVA) model of speech production (Tourville and Guenther, 2011). According to the DIVA model, there is a set of projections to the bilateral ventral motor cortex that represent a set of feedforward motor commands for articulatory gestures for a set of speech sounds. An active speech sound map cell sends input to the feedforward motor control pathway for the production of a learned speech sound. For older children, production of speech has become adult-like (Hoit et al., 1990). For the speech tasks in the present study, these older children may have invoked a feedforward loop as evidenced by high peak coherence values, regardless of requirements for increased vocal loudness. However, for younger children, considerably lower coherence values were observed for speech tasks. In this case, the speech sound map in the DIVA model also projects to auditory and somatosensory regions in a feedback loop, which likely supports the integration of speech motor commands in this younger group who are still going through speech motor control refinement (Tourville & Guenther, 2011).

Task Specificity

We hypothesized that younger children would exhibit lower intermuscular coherence values across all tasks, regardless of volume and/or alveolar pressure targets, indicating a lack of task specific muscle coordination. In contrast, we hypothesized that older children would exhibit changes in intermuscular coherence based on task-specific features of skill and strength. The coherence pattern, shown in *Figure 13*, and the interactions shown between children within each age group in *Figures 14 and 15* indicate that some level of task specificity was found for both age groups. Eight significant task specific differences were found within the younger group of children, and thirteen significant task specific differences were found within the older group of children. While results indicate that both age groups of children display task specific muscle coordination patterns, there are notable developmental differences when tasks are viewed based upon the natural separation of two skill levels: over-learned and novel.

Task specific differences for younger children occur only between over-learned and novel tasks (e.g., between VC and SP). In comparison, older children also display task specific differences within novel tasks (e.g., between VC and PH). Task specific differences were not found between speech tasks and rest breathing, in line with findings from Smith and Denny (1990) who reported similar coherence values for speech tasks compared to breathing tasks in healthy adults in the 20-60 Hz bandwidth. Older children, who have developed adult-like speech breathing patterns, display muscle coordination patterns in-line with a more refined level of task specificity than their younger counterparts.

Task specific muscle coordination patterns are supported by interpretation of the dynamical systems theory with respect to motor control. Under the dynamical systems theory, the human movement system is a highly intricate network of co-dependent sub-systems (e.g., respiratory, circulatory, nervous, skeletomuscular and perceptual) that cooperatively function together to form movement patterns through generic processes of self-organization to meet the demands of the environment (Glazier et al., 2003). Bernstein (1967) defines movement coordination as the mastering of redundant degrees of freedom in a system. Task specific, consistent movement patterns arise out of the development of functionally preferred coordination or attractor states that support goal-directed actions (Glazier et al., 2003). Within each attractor region, system dynamics are highly ordered and stable. Coordination dynamics arising from dynamical systems theory have previously been applied to sports related coordination studies (Davids et al., 2005). In the present study, both older and younger children demonstrated task-specific differences in muscle coordination between over-learned and novel tasks. Despite developmental changes continuing to occur for speech breathing in younger children, task specific muscle coordination is evident, though less specific than for older children. Under the dynamical systems theory, free exploration of performance contexts by each individual is permitted resulting from variation between multiple attractor regions that allows for flexible and adaptive motor system behavior, (Glazier et al., 2003). Younger children may be continuing to undergo a greater amount of exploration in motor control for muscle coordination as they move towards an adult-like model of speech breathing whereas older children have developed task specific coordination patterns for tasks ranging in lung volume excursion and alveolar pressures.

Limitations

In the current study, sentence repetitions were utilized as the only source of speech breathing tasks analyzed. Findings for developmental differences in terms of lung volume events were not evident. Comparatively, previous speech breathing literature (Boliek, et al., 1996, 1997 & 2009; Hoit et al., 1990; Stathopoulos and Sapienza, 1993 &1997) and general consensus in the field, concludes that children undergo developmental changes in the refinement of speech breathing throughout childhood, developing an adult-like model of speech breathing by the age of 10 years (Hoit, 1990). Sentence repetitions, utilized in the present study, offered a constrained format of speech production and resultant speech breathing measurements. A developmental age difference was not found for speech breathing. Prior to completion of the manuscript for publication, conversational speech breathing measures, which represent a more idealistic speech phenomenon, will be analyzed and included. Despite findings in the present study that a developmental age difference does not exist for lung volume events on speech sentence repetition tasks, previous findings support that children do undergo developmental changes for speech breathing. This provides a foundation to support the present finding that there are similar age-related changes in intermuscular coherence, during speech breathing tasks.

Future Directions

Findings in the present study lead to hypotheses for future research in the area of intermuscular coherence associated with speech breathing development and its relation to integrity of the corticospinal tract and neuromuscular control. There is currently a lack of research exploring the linearity between measurements of corticomuscular and intermuscular coherence (Maurer et al., 2013) and an ongoing discussion regarding the use of intermuscular coherence as a measure of cortical drive (Boonstra, 2013). Further evidence is required to show that the frequency signal between EEG-EMG and EMG-EMG activity holds the same modulatory meaning. Evidence that intermuscular coherence represents descending neuromuscular modulation through the corticospinal tract has been found in adult populations (Hansen et al., 2005; Norton & Gorassini, 2006; Fisher et al., 2012). However, correlation between corticospinal tract integrity and strength of intermuscular coherence measurements in developing children has not been done. Future research examining this relationship will allow for direct inferences to be made about the magnitude of cortical involvement relative to measured intermuscular coherence at the periphery. Based on current findings, we hypothesize that future research may show that increased intermuscular coherence, associated with greater muscle coordination, represents a common, task dependent, neuromuscular drive through the corticospinal tract. Similarly, decreased intermuscular coherence, which is associated with lower muscular coordination, would represent recruitment of a more distributed neural control network through the corticospinal tract. Research linking intermuscular coherence to corticospinal tract integrity in developing children would provide a robust contribution to this field of literature.

The present study was conducted in conjunction with two other studies: determining the differential effects of lung volume and pressure loading of the chest wall on intermuscular coherence of the chest wall for non-speech and speech tasks in healthy individuals. Additional work is underway to examine the effects of transcranial direct current stimulation (tDCS) on intermuscular coherence in healthy younger and older adults, to enhance our understanding of speech motor control in relation to control of the other speech subsystems. Together these three studies will complete an in-depth examination of intermuscular coherence for speech breathing in child and adult populations and provide a database for future experimental comparison. The findings gained from the healthy participants studied will be applied to therapeutic interventions for patients suffering from neuromuscular motor speech disorders involving the respiratory and laryngeal subsystems. Characterization of intermuscular coherence for speech breathing in disordered populations (e.g., Cerebral Palsy), is a suitable next step in order to expand our understanding of intermuscular coherence and muscle coordination patterns in these individuals as we work towards developing targeted, disorder specific, therapeutic interventions.

Conclusions

To our knowledge, this was the first study of its kind to investigate developmental changes in intermuscular coherence measurements for tasks varying in lung volume and alveolar pressure requirements. Findings in the present study suggest that consistent with changes in speech breathing during development from childhood to adolescence, children are also undergoing age related changes in intermuscular coherence for speech breathing. In addition, older and younger children show an intermuscular coherence preference for task specificity during both non-speech and speech breathing but older children exhibit greater refinement of this task specificity. Older children exhibit increased intermuscular coherence and greater muscle coordination during speech breathing whereas younger children in comparison exhibit decreased intermuscular coherence and a lower amount of muscle coordination. For non-learned, non-speech tasks requiring maximal lung volume and/or pressure generation, both older and younger children display decreased muscle coordination in line with a still developing model.

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