Title: A descriptive study of speech breathing in children with cerebral palsy during two types of connected speech tasks

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Abstract

Purpose: The present study examined speech breathing during two connected speech tasks in children with cerebral palsy (CP) and typically developing (TD) peers. Understanding how the respiratory system supports speech production during various speech tasks can help researchers to construct appropriate models of speech production and clinicians to remediate speech disorders effectively.

Method: Four children with CP and four age- and sex-matched TD peers completed two speech tasks, reading and extemporaneous speech. Respiratory kinematic and acoustic data were collected. Dependent variables included utterance length, speech rate, sound pressure level, and lung volume variables.

Results: Based on descriptive results, children with CP and speech motor involvement demonstrated reduced utterance length and speech rate, equivalent intensity levels, and changes in lung volume variables indicative of respiratory physiologic impairment as compared to TD peers. However, children with CP and no speech motor involvement exhibited speech production and speech breathing variables in the more typical range. In relation to task effects, the majority of children (CP and TD) produced shorter utterances, slower speech rates, equivalent intensity levels, higher lung volume initiation, termination, excursion, higher percent vital capacity per syllable, and longer inspiratory duration during extemporaneous speech as compared to reading.

Conclusion: Two major themes emerged from the data: 1) Children with CP, particularly those with concomitant speech motor involvement, demonstrate different speech production and speech breathing patterns than TD peers and 2) Speech task impacts speech production and speech breathing variables in both children with CP and TD peers, but the extemporaneous speech task did not seem to exaggerate group differences.

Introduction

Cerebral palsy (CP) is a heterogeneous group of disorders characterized by Rosenbaum and colleagues (2007) as nonprogressive movement and posture disturbances resulting from abnormal fetal or infant brain development and often co-occurring with deficits in sensation, perception, cognition, communication, and behavior. The most common cause of severe motor disability in children, CP is estimated to occur in approximately 2.9 per 1000 children (Durkin et al., 2016). Of the various comorbidities that children with CP may experience, speech motor involvement (i.e., dysarthria) was of specific interest to this study. Speech motor involvement is estimated to occur in approximately half of children with CP (Nordberg et al., 2014). Hustad (2010) defines speech motor involvement as “any evidence of motor impairment in any one or more of the speech subsystems (articulation, phonation, resonation, respiration) that can be observed at rest, during speech, or during feeding” (p. 367) and includes excessive drooling, and facial asymmetry. Speakers with CP tend to have speech deficits that involve all speech subsystems to varying degrees (Hustad, 2010).

While speech motor involvement may result in deficits in any single or combination of speech subsystems, the present study focused specifically on the respiratory subsystem. The respiratory subsystem provides the driving pressure required to produce speech. Respiratory physiologic impairments contribute to auditory-perceptual features of speech motor involvement such as inappropriate phrasing, reduced stress, voice quality changes, and difficulties regulating loudness, all of which are common in children with CP (Haas et al., 2021; Workinger & Kent, 1991). Respiration for speech, or speech breathing, is a carefully regulated process. Speech breathing is “the respiratory mechanics used to inhale before speaking and to generate and maintain subglottal air pressure during speech production” (Solomon & Charron, 1998, p. 61).

Passive and active forces within the respiratory system must be balanced to support speech (Huber & Stathopoulos, 2015). At rest, the lung volume is at end expiratory level, or “the point in the respiratory cycle at the end of a tidal expiration” (Huber & Stathopoulos, 2015, p. 14). During inspiration, lung volume exceeds end expiratory level, generating a positive recoil force (Hixon & Hoit, 2005). This positive recoil force helps return the lung volume to end expiratory level during expiration. As one expires below end expiratory level, negative recoil force is generated (Hixon & Hoit, 2005). This negative recoil force assists the lungs in expanding to return to end expiratory level. These recoil forces are passive; that is, they are not produced by muscle contraction, but rather the elastic properties of the lung-thorax unit. Recoil forces are greater the farther the lung-thorax unit is from rest (Zapletal et al., 1976). Respiratory muscles are used to apply active force to the respiratory system during speech production. Active muscular force is necessary when passive recoil forces are either too high or too low to generate the pressure needed for the demands of speech production (Hixon & Hoit, 2005). For example, active muscular forces are solely responsible for pressure generation for speech production below end expiratory level since passive recoil forces are working to expand and not contract the lungs. Generating active muscular force requires work, so the more active muscular force that is needed to produce speech, the more work an individual performs. Doing more work is perceived as more effortful.

Children with CP experience physiologic changes that likely lead to an overreliance on active forces during speech production (Dias & de Lima, 2021; Solomon & Charron, 1998). Spasticity is the most commonly occurring tonal/movement abnormality affecting approximately 70-80% of children with CP (Stanley et al., 2000). Children with spastic CP generally display “increased muscle tone, hyperactive reflexes, abnormal patterns of posture or movement, and increased resistance to externally imposed movement" (Hustad, 2010, p.361). Spasticity of the chest wall leads to decreased chest mobility (Ersoz et al., 2006). Decreased chest mobility may lead to difficulties initiating speech at higher lung volumes and an inability to capitalize on passive recoil pressure during speech production. Uncoordinated, paradoxical movements of the chest wall are more likely to be present in children with CP (Hull & Bryngelson, 1941). This means that the chest wall may be expanding outward while lung volume is decreasing, or the chest wall may be compressing inward while lung volume is increasing. This paradoxical movement is highly inefficient for speech production. Active muscle forces would be required throughout the speech breathing cycle in order to maintain adequate pressure for speech production in the fact of paradoxical chest wall movements. Further, children with CP exhibit inefficient valving of the airstream by the larynx, velopharynx, and orofacial articulators (Hardy, 1967). Inefficiencies in valving may lead to air wastage requiring greater lung volume excursions and active muscle forces to support those excursions.

Due to the inherent neuromuscular impairments of the disorder, respiratory kinematic data demonstrate that children with CP utilize different respiratory patterns during speech production than typically developing children (Clair-Auger et al., 2015; Edgson et al., 2021; Redstone, 2004). Studies that examine simultaneous lung volume and respiratory muscle activation during speech production in children with CP support the hypothesis that the physiologic impairments detailed above result in an overreliance of active muscle forces during speech production (Clair-Auger et al., 2015; Edgson et al., 2021). Edgson and colleagues (2021) found that children with CP do not initiate speech at higher lung volumes when increasing vocal loudness, as was seen in typically developing peers, but rather increased intercostal and oblique muscle activity. Relying on active muscle forces, however, is not an efficient strategy since respiratory muscle weakness is common in children with CP (Hardy, 1961, 1967; Wang et al., 2012). Overall, speech production in children with CP is effortful and fatiguing. Thus, it is likely that children with CP have a decreased functional capacity for speech production.

Unfortunately, there is a dearth of literature regarding speech breathing in children with CP, particularly in ecologically valid tasks like reading and extemporaneous speech. As a result, there are no evidence-based interventions that directly target speech breathing behavior in children with CP. To our knowledge, only three peer-reviewed studies exist that report respiratory kinematic data during speech production in children with CP. These studies include a total of 15 children with CP, five between the ages of 8 and 12 (Clair-Auger et al., 2015; Edgson et al., 2021) and ten between the ages of 4 and 5 (Redstone, 2004). Further, these studies include only one speech task, single sentence repetition (Clair-Auger et al., 2015; Edgson et al., 2021; Redstone, 2004). While speech breathing data in reading and extemporaneous speech do not exist for children with CP, these data do exist for typically developing children (Hoit et al., 1990). The primary purpose of Hoit et al. (1990) was to examine speech breathing performance during a reading and extemporaneous speech task in 7-, 10-, 13-, and 16-year-olds and identify any sex- and age-related differences. In general, findings revealed minor differences related to sex, but substantial differences related to age. Based on these data, speech breathing patterns are not adult-like until age 10 and variables related to syllable production, like percent vital capacity per syllable, are not adult-like until age 16. After age 10, speech is typically initiated above end expiratory level and terminated at or just below end expiratory level. No statistical tests were performed to examine differences in speech breathing patterns between speech tasks.

Speech motor control in children is heavily influenced by cognitive-linguistic load (e.g., language formulation requirements; e.g., Darling-White & Banks, 2021; Goffman, 2010;

Haselager et al., 1991; Mahr et al., 2021; Nip & Green, 2013; Sadagopan & Smith, 2008; Saletta et al., 2018; Vuolo & Goffman, 2018). For example, speech rate is slower during speech tasks with more demanding language formulation requirements (Haselager et al., 1991; Logan et al., 2011; Nip & Green, 2013). Speech breathing variables are an adequate method for examining the interaction between cognitive-linguistic factors and respiratory physiologic factors during speech production (Huber & Darling, 2011). If speech production is already effortful for children with CP in single sentences, then speech tasks that demand more language formulation and more respiratory physiologic requirements (e.g., several utterances produced in a row) may exacerbate speech breathing impairments. It is important to understand how the respiratory system adjusts during various speech tasks in order to construct appropriate models of speech production and effectively provide intervention (Huber & Stathopoulos, 2015). For example, school-age children need to produce speech when responding to questions in the classroom, reading aloud, or interacting with peers. It is unlikely that all these instances require only a few words produced on a single breath with time for a rest between utterances as is the case in a sentence repetition task. Knowing how speech breathing is impacted by ecologically valid tasks, like reading and extemporaneous speech, in children with CP will provide insight into how these children function in their daily lives.

The current study presents speech breathing data from two types of connected speech tasks, reading and extemporaneous speech, from four children with CP and four age- and sex-matched peers. We will descriptively discuss both group and task differences. The limited previous research makes it difficult to formulate directional hypotheses regarding speech breathing. However, given what is known about auditory-perceptual impairments in children with CP, children with CP will likely demonstrate differences in utterance length, speech rate, and lung volume measures as compared to age- and sex-matched peers. These differences will likely be exacerbated by the extemporaneous speech task.

Methods

Participants

Approval for all study procedures was obtained by the University of Arizona Human Subjects Review Board (Protocol 16055837A005). Eight children were included in the present study: four children with CP and four age- and sex-matched TD peers. These participants were part of a larger parent study (see Darling-White (2022)). Data presented in the current study are unique. Children with CP were recruited through specialty clinics and public postings. All TD children were recruited through postings in the community and on public websites. Written consent from legal guardians and verbal assent from participants were obtained before data collection was initiated.

Children with Cerebral Palsy

The following inclusionary criteria were required for the larger parent study: (a) be between the ages of 8 and 17 years, (b) be fluent American English speakers, (c) communicate verbally as the primary mode of communication, (d) be able to follow basic directions to complete experimental tasks, and (e) have no history of head, neck, or chest cancer or surgery. To be included in the current study, children with CP had to have completed both the reading and extemporaneous speech tasks (described below) while wearing the respiratory kinematic bands. Four children with CP (two males and two females) met these requirements. See Table 1 for a detailed description of age, language impairment status, speech motor status and characteristics, intelligibility, and gross motor function for each child with CP.

A certified speech-language pathologist (the second author) determined the presence or absence of speech motor involvement (i.e., dysarthria) using standard clinical procedures relying on perceptual assessment. Two children with CP demonstrated speech motor involvement and two children with CP did not. The primary speech characteristics and the overall severity of speech motor involvement of the two children with CP and speech motor involvement are detailed in Table 1. The dichotomous classification of children with CP as having or not having speech motor involvement is based on the Speech Language Profile Groups (SLPG) paradigm developed by Hustad and colleagues (Hustad et al., 2010). The SLPG is a classification system based on behavioral speech and language assessment data as well as speech intelligibility that has been validated and replicated (Hustad et al., 2010, 2016). It is easy to assume that children with CP and no speech motor involvement produce speech in the same manner as typically developing children. However, this does not appear to be the case. Children with CP and no speech motor involvement demonstrate differences in speech production and reductions in speech intelligibility relative to their typically developing peers (Hustad et al., 2012, 2019). No speech breathing data exist for children with CP and no speech motor involvement. Given that the muscles of the respiratory subsystem are impacted by spasticity and other tonal impairments in a different way than the oral-motor musculature, it is possible some of the differences in speech production observed between children with CP and no speech motor involvement and typically developing children are related to differences in respiratory support during speech production. Thus, children with CP and no speech motor involvement were included in the current study.

All participants had normal hearing as evidenced by passing a pure-tone hearing screening at 20 dB HL for 500, 1000, 2000, and 4000 Hz. Children’s core language score on the

Clinical Evaluation of Language Fundamentals-Fifth Edition (CELF-5; Wiig et al., 2013) was used to determine the presence or absence of a language impairment. The core language score of the CELF-5 is based on performance during four subtests: formulate sentences, recalling sentences, understanding spoken paragraphs, and semantic relationships. Participant M08CP, whose first language was Chinese and who had been learning American English for approximately 3 years, was not given the CELF-5 as it was deemed inappropriate. However, there were no parent reports of language impairment. M08CP was fluent in American English at the time of data collection and was able to follow all directions to participate in the study.

Eighty adult listeners (20 listeners per child) provided orthographic transcriptions of the sentence-level Test of Children's Speech (*TOCS*+; Hodge & Daniels, 2009). The *TOCS*+ software generates unique lists containing 34 sentences, ranging from two- to seven-words in length. Each child with CP produced a different list of sentences. Participants repeated each stimulus sentence using their comfortable pitch and loudness following a prerecorded adult model (the second author). Stimulus sentences were presented, both visually and auditorily, via a laptop computer. Listeners were recruited from Amazon Mechanical Turk (MTurk), an online crowdsourcing platform. The use of crowdsourcing platforms, such as MTurk, in auditory-perceptual studies in the speech sciences have been validated (Lansford et al., 2016; McAllister Byun et al., 2015) and are becoming more frequent in the literature (e.g., Borrie et al., 2017; Jiao et al., 2019; McAllister Byun, 2017; McAllister Byun et al., 2016; Nightingale et al., 2020). The requirements to participate in the listening study were as follows: 1) Be designated by Amazon as a Master (i.e., have high approval ratings), 2) Have a U.S.-based IP address, 3) Use Firefox, Chrome, or Safari browsers, 4) Be between the ages of 18 and 45 years, 5) Be a native speaker of American English, 6) Have no history of speech, language, learning, or hearing disorders, 7)

Have no more than incidental experience listening to children with speech sound disorders, and 8) Have a pair of headphones to complete the task. The study was conducted via a Qualtrics survey and took approximately 30 minutes. Listeners were compensated $5 for their time. Listeners were instructed they would hear a child produce different sentences and were asked to type the words they heard in the textbox provided. Listeners were told the sentences contained only English words and were encouraged to guess if they were unsure. Throughout the study, listeners were reminded to use a pair of headphones set to a comfortable loudness output level. Listeners heard each sentence one time. Prior to administration, sound files were amplitude normalized via a customized MATLAB script. Listeners were given eight practice trials prior to the experiment to acclimate to the task. The practice sentences were produced by typically developing children of approximately the same age. None of the sentences in the practice trials appeared in the *TOCS+*. Listeners were not given feedback on their practice trials. To have their data included in the study, each listener was required to obtain at least 75% accuracy on the practice trials. Listener responses were scored by a team of two to four undergraduate research assistants and scoring discrepancies were resolved via consensus. Responses were scored as correct if they were an exact phonemic match with the target. Homonyms and misspellings were counted as correct as long as they were an exact phonemic match with the target. A %intelligible score was calculated for each listener's responses by adding the number of words correctly identified, dividing by the total number of words, and multiplying by 100. The %intelligibility score presented in Table 1 was obtained by averaging the % intelligibility score across all 20 listeners for each participant.

Gross motor function was characterized for the children with CP via parent report. Tonal/movement abnormalities (e.g., spastic), topographical distribution (e.g., diplegia and hemiplegia), and scores on the Gross Motor Function Classification System (GMFCS; Palisano et al., 1997) are reported in Table 1. The GMFCS is a standard measurement tool designed for children with CP that classifies gross motor abilities into five levels. GMFCS Level I represents the least impairment (i.e., the child can walk, run, climb stairs, and jump independently, but the child may be limited in speed, balance, and coordination), and GMFCS Level V represents the greatest impairment (i.e., the child requires a manual wheelchair for transport in all settings, and the child is limited in resisting gravity for head and trunk postures and in controlling limb movements).

Lung function was examined to ensure the health of the participants' lungs prior to data collection. To test vital capacity (VC) and forced vital capacity (FVC), each participant completed 1-2 trials of each maneuver while breathing into a digital spirometer (VacuMed Discovery Handheld Spirometer). For the VC maneuver, participants were instructed to inspire as much air as possible and then expire as much air as possible. For the FVC maneuver, participants were instructed to inspire as much air as possible and then expire as hard and fast as possible. During these maneuvers, the second author held the digital spirometer and encouraged the participants to produce each task to their maximum capability. Normal lung function was defined as VC and FVC values that were greater than or equal to 80% of expected values based on age, sex, height, and weight coded into the spirometer (VacuMed Discovery Handheld Spirometer). Children with CP were not required to have normal lung function. Three of the four children with CP demonstrated normal lung function. One participant (F01CP) did not participate in lung function testing, but did not have any reported chronic or acute respiratory illness.

Age- and Sex-Matched Typically Developing Peers

Four age- and sex-matched TD children were included in the present study. To be included in the larger parent study, TD children needed to (a) be between the ages of 8 and 17 years, (b) be fluent American English speakers, (c) have no reported history of speech, language, hearing, or learning problems, (d) have normal speech, language, and hearing, (e) demonstrate normal lung function based on their age, sex, height, and weight, and (f) have no history of head, neck, or chest cancer or surgery. To be chosen as an age- and sex-match for a CP participant in the current study, TD children had to have completed both the reading and extemporaneous speech task (described below) while wearing the respiratory kinematic bands.

Perceptual assessment by a certified speech-language pathologist (the second author) determined that all TD children had typical speech production and voice quality. All TD children scored within the average or above average range on the subtest that combine to provide the core language score of the CELF-5 (Wiig et al., 2013). All TD children were determined to have normal lung function based on the procedure described above.

Equipment and Data Collection

Data collection took place over two sessions, roughly 1 week apart, as part of the larger parent study. Respiratory and acoustic data presented in this study were collected at the Motor Speech Research Laboratory at the University of Arizona during one of these sessions. Data collection took approximately 60 minutes. Frequent breaks were provided to prevent fatigue. At the time of data collection, participants were free of allergies or cold symptoms.

Speech Stimuli

Each participant completed two speech tasks, a reading task and an extemporaneous speech task, using a comfortable loudness and pitch, while wearing the microphone and respiratory kinematic bands (described below). For the reading task, participants were asked to read "The Caterpillar" (Patel et al., 2013) aloud, the text of which was displayed on a computer monitor approximately 2ft. away. None of the participants reported visual impairment. "The Caterpillar" passage has a Flesh-Kincaid reading grade level of 5.0. Per parent report, all participants read at a level of 5.0 or higher. Each participant was given the opportunity to practice the passage aloud one time prior to data collection. Based on this practice trial, the second author determined that each participant could read the passage fluently. For the extemporaneous speech task, children were asked to speak about a topic of their choice (e.g., a favorite book or movie, their family, school) for about 2 min.

Acoustic Data

An omnidirectional headset microphone (Shure WBH53) with a flat frequency response up to 20 kHz was used to transduce the acoustic signal. The microphone was held at a constant distance of 6 cm from the participant's mouth. The microphone signal was recorded to a digital audio recorder (Marantz PMD-671) with a compact flash card and was later transferred to a computer. Goldwave was used to resample the acoustic signal at 18 kHz with a low-pass filter at 9 kHz for anti-aliasing. The microphone was calibrated before each participant using a pure-tone generator and sound level meter in a manner similar to Method 2B outlined in Švec and Granqvist (2018). The difference between the measured intensity of the calibration signal in Praat (Boersma & Weenink, 2020) and the measured intensity of the calibration signal from the sound level meter was calculated and added to the intensity measures detailed below.

Respiratory Kinematic Data

Respiratory inductive plethysmography (Inductotrace, Ambulatory Monitoring Inc.) was used to collect respiratory kinematic data. Two elastic bands, one placed around the rib cage inferior to the axilla, and one placed around the abdomen at the level of the navel, inferior to floating ribs, were used to transduce the movement of the rib cage and the abdomen. LabChart (ADInstruments) digitized the respiratory kinematic data using a sampling rate of 1 kHz/s. The acoustic and respiratory kinematic signals were time-locked via LabChart.

Once the bands were placed appropriately, participants engaged in a series of calibration tasks. Correction factors for the rib cage (RC) and abdomen (AB) were calculated from the rest breathing calibration task using the least squares method. For the rest breathing calibration task, participants wore nose clips and breathed quietly through a digital spirometer over two 45-s trials for a total of 1.5 mins. The correction factors for the RC signal (k1) and the AB signal (k2) were solved for using a Moore-Penrose pseudoinverse function in the following formula:

$$\text{Spirometer (L)} = k1\ (RC) + k2\ (AB)$$

The correction factors for the RC and AB signal were then used to estimate lung volume during speech tasks. This method has been validated for children with CP and typically developing children (Darling-White, 2022).

Measurements

Speech Production Measures

The speech production measures used were utterance length, speech rate, and sound pressure level. Utterance length was defined as the number of syllables per breath. Praat (Boersma & Weenink, 2020) was used to visually inspect the acoustic data and to determine the number of syllables. A syllable had to contain one vowel to be counted as a syllable. Diphthongs were counted as one syllable. Prolonged vowels were determined to be one syllable if the vowel remained constant or part of a diphthong. Single vowels that were repeated (e.g., "e-e-e-even") were counted as separate syllables. Syllabic /n/ and /l/ were counted as syllables. Speech rate was defined as the number of syllables per utterance divided by utterance duration (syllables/second).

Syllables were manually entered in the custom, semiautomated MATLAB program used to measure the respiratory kinematic measures described below. Utterance length and speech rate were calculated using this program. The duration of the utterance (i.e., the amount of time between the initiation and termination of speech) was identified in MATLAB using the time-locked acoustic signal.

Sound pressure level was calculated as the mean intensity (dB) of each speech segment produced during the task exclusive of pauses. The spectrogram displayed in Praat was used to identify when the participant was speaking and when they were pausing. A pause was defined as a period of silence 0.15 seconds or longer. Each pause and speech segment were marked in the textgrid. A customized MATLAB program was used to extract the mean intensity (dB) from each speech segment based on the labels from the textgrid.

Respiratory Kinematic Measures

Respiratory kinematic data were analyzed in custom, semiautomated MATLAB programs. Prior to all measurements, the program prompted the user to mark the end expiratory level from three rest breaths collected immediately prior to the start of the speech task. End expiratory level was defined as the average of these three troughs. To account for any body movements between speech tasks that could result in a shift of end expiratory level, end expiratory level was calculated for each speech task separately. Body movement was carefully monitored during data collection by the second author. Children were instructed to remain as still as possible during the speech task. If large body movements were observed, the speech task was stopped and collected again without body movement. This did not occur for any of the children in the present study.

All respiratory measurements were expressed as a % of VC relative to end expiratory level. Prior to the speech tasks, participants performed VC maneuvers while wearing the respiratory bands. VC maneuvers were elicited in the manner described above. The second author monitored performance and determined when each participant had produced a VC maneuver to their maximum capability. This generally occurred within one to three trials. VC was measured from the peak of the inspiratory phase of the maneuver to the trough of the expiratory phase of the maneuver. After hand-picking the peak and trough for the VC maneuver, the MATLAB program computes the VC by subtracting the value of the trough from the value of the peak. This VC value is compared to any subsequently measured VC maneuver. In the case where more than one VC maneuver was measured, the MATLAB program chooses the best maneuver (i.e., largest VC value) to use for further calculations. Utilizing the calculated VC, the MATLAB program converted the end expiratory level measured prior to the start of each speech task to represent 0%VC. For all respiratory kinematic measures, positive values indicate lung volumes above end expiratory level and negative values indicate lung volumes below end expiratory level. This methodology appears in the majority of speech breathing literature from the past 15 years (e.g., Darling-White & Huber, 2017; Huber, 2007, 2008; Huber & Darling, 2011; Huber & Darling-White, 2017; Sadagopan & Huber, 2007; Stathopoulos et al., 2014).

The respiratory kinematic measures used were inspiratory duration, lung volume initiation, lung volume termination, lung volume excursion, and percent vital capacity per syllable. Inspiratory duration was defined as the amount of time in seconds spent inspiring before each utterance. This was manually measured as the trough of the previous expiration to the peak of the inspiration of the utterance being measured. Lung volume initiation (LVI) was defined as the lung volume at the onset of speech for a particular utterance. Lung volume termination

(LVT) was defined as the lung volume at the offset of speech for a particular utterance. The time-locked acoustic signal was used as a guide for these measures. Lung volume excursion (LVE) was defined as the difference between LVI and LVT. Lung volume measures were expressed as a % of VC. Percent vital capacity per syllable (%VC/syll) was defined as the amount of lung volume used for each syllable and was calculated by dividing LVE by the number of syllables in a given utterance. Any utterance with a cough or laugh was excluded from the measurements.

Statistical Analysis

Descriptive results (means and standard errors) for each measure were calculated for each participant and are presented below. No inferential statistics were calculated given the small sample size.

Results

Descriptive results are reported below in pairs of participants. Each pair contains one CP participant and their age- and sex-matched TD peer. For each pair, results are discussed relative to within-participant task differences and between participant differences. Figure 1 depicts LVI, LVT, and LVE for each pair. Tables 2 – 5 contain means and standard errors for all dependent variables for each pair. Table 6 provides a summary of participant comparisons.

Pair 1: F01CP and F17TD

F01CP: Reading vs. Extemporaneous Speech

This child was a 13-year-old female with spastic, diplegic CP and concomitant speech motor involvement and language impairment. F01CP produced shorter utterances in the extemporaneous speech task than in the reading task. The difference in speech rate between the tasks was slight (MD = 0.06 syll/sec), with extemporaneous speech being produced slower than reading. It is unlikely that such a small difference in speech rate drove the 3 syllable per utterance mean difference in utterance length between the tasks. Across both tasks, F01CP produced almost the same intensity level (MD = 0.09 dB), so the lung volume changes discussed below were not driven by changes in intensity but rather were the likely product of task differences. F01CP demonstrated higher LVI, LVT, LVE, and %VC/syll, and longer inspiratory duration during extemporaneous speech than in reading.

F17TD: Reading vs. Extemporaneous Speech

This child was a 13-year-old typically developing female. F17TD produced shorter utterances in extemporaneous speech than in reading. Similar to F01CP, difference in speech rate between the tasks (MD = 0.97 syll/sec), with extemporaneous speech being produced slower than reading, did not likely drive the 7.84 syllables per utterance mean difference in utterance length between the tasks. F17TD produced a slightly lower intensity (MD = 1.5 dB) in extemporaneous speech than in reading. While this could impact lung volume, the lung volume differences across tasks are the opposite of what we would expect when someone uses a lower intensity. So it is unlikely the lung volume changes discussed below were driven by changes in intensity, but rather were the likely product of task differences. F17TD demonstrated higher LVI and LVT, lower LVE, higher %VC/syll, and longer inspiratory duration during extemporaneous than during reading.

Comparison of F01CP to F17TD

Participant comparisons. Across tasks, F01CP demonstrated differences in speech production and speech breathing behavior as compared to F17TD. F01CP produced shorter utterances, slower speech rate, lower LVI, LVT, and LVE, higher %VC/syll, and longer inspiratory duration. The only similarity was SPL, which was almost identical.

Task comparisons. F01CP and F17TD demonstrated very similar changes in speech production and speech breathing patterns across tasks. Both subjects decreased utterance length, produced similar speech rates and intensities, increased LVI, LVT, and %VC/syll, and produced longer inspiratory durations during extemporaneous speech. The only difference in task patterns was for LVE.

Pair 2: F02CP and F38TD

F02CP: Reading vs. Extemporaneous Speech

F02CP was a 14-year-old female with spastic, hemiplegic CP, no speech motor involvement and no language impairment. F02CP produced shorter utterances (MD = 3.36 syll) and a slower speech rate (MD = 1.84 syll/sec) in extemporaneous speech than in reading. In addition to task effects, it is likely that the slower speech rate during extemporaneous speech contributed to the reductions in utterance length. F02CP produced a slightly lower intensity (MD = 1.06dB) in extemporaneous speech than in reading. While this could impact lung volume, the lung volume differences across tasks are the opposite than we would expect when someone uses a lower intensity. So it is unlikely the lung volume changes discussed below were driven by changes in intensity, but rather were the likely product of task differences. F02CP demonstrated higher LVI, LVT, LVE, and %VC/syll, and longer inspiratory duration during extemporaneous speech than during reading.

F38TD: Reading vs. Extemporaneous Speech

F38TD was a 13-year-old typically developing female. F38TD produced longer utterances in extemporaneous speech than in reading. The slight difference in speech rate between the tasks (MD = 0.80 syll/sec), with extemporaneous speech being produced slower than reading, did not likely drive the 3.59 syllables per utterance mean difference in utterance length between the tasks, so differences in utterance length were likely related to the task itself. F38TD produced a lower intensity (MD = 4.38 dB) in extemporaneous speech than in reading. It is possible that changes in intensity, in addition to task effects, contributed to lung volume differences since the differences in LVI and LVT follow the pattern we would expect when someone speaks with a lower intensity. F38TD demonstrated lower LVI and LVT and higher LVE and %VC/syll, and longer inspiratory duration in extemporaneous speech than in reading.

Comparison of F02CP to F38TD

Participant comparisons. F01CP demonstrated similarities and differences in speech production and speech breathing behavior as compared to F38TD. Several of these differences appeared to be mediated by task. F02CP produced longer utterances in reading, but slightly shorter utterances in extemporaneous speech as compared to F38TD. F01CP produced a faster speech rate in reading, but a slower speech rate in extemporaneous speech than F38TD. Across both tasks, F02CP demonstrated a lower intensity. F02CP demonstrated higher LVI, LVT, and LVE than F38TD across tasks. F02CP produced slightly lower %VC/syll in reading, but higher %VC/syll in extemporaneous speech than F38TD. Across tasks, F02CP demonstrated longer inspiratory duration than F38TD.

Task comparisons. F02CP and F38TD demonstrated similarities and differences in speech production and speech breathing behavior across tasks. Similarities included decreased speech rate, increased LVE and %VC/syll, and longer inspiratory duration in extemporaneous speech than in reading. Different patterns were observed for utterance length, SPL, LVI, and LVT.

Pair 3: M04CP and M43TD

M04CP: Reading vs. Extemporaneous Speech

This child was an 11-year-old male with spastic CP, no speech motor involvement, and no language impairment. M04CP demonstrated similar utterance lengths for each task, though utterance lengths in the extemporaneous speech task were slightly shorter than in reading (MD= 0.96 syll). This difference in utterance length was likely due to his slower rate in the extemporaneous speech task than in reading (MD = 0.81 syll/sec). M04CP produced a slightly higher intensity (MD = 2.87dB) in extemporaneous speech than in reading. It is possible that changes in intensity, in addition to task effects, contributed to lung volume differences across tasks since lung volume differences follow the pattern we would expect when someone speaks with a higher intensity. M04CP demonstrated higher LVI and LVT, lower LVE, and higher %VC/syll in extemporaneous speech than reading. M04CP produced approximately the same inspiratory duration (MD = 0.03 sec) across tasks.

M43TD: Reading vs. Extemporaneous Speech

This child was an 11-year-old typically developing male. M43TD had shorter utterances in extemporaneous speech than in reading. The slight difference in speech rate between the tasks (MD = 0.43 syll/sec), with extemporaneous speech being produced slower than reading, did not likely drive the 2.09 syllables per utterance mean difference in utterance length between the tasks, so differences in utterance length were likely related to the task itself. Across both tasks, M43TD produced almost the same intensity level (MD = 0.21 dB), so the lung volume changes discussed below were not driven by change in intensity but rather were the likely product of task differences. M43TD demonstrated higher LVI and LVT, lower LVE, higher %VC/syll, and longer inspiratory duration in extemporaneous speech than reading.

Comparison of M04CP to M43TD

Participant comparisons. M04CP demonstrated similarities and differences in speech production and speech breathing behavior as compared to M43TD. A few of these differences appeared to be mediated by task. M04CP produced longer utterances and a faster speech rate than M43TD for both tasks. Across tasks, M04CP and M43TD produced similar intensity levels as one another. M04CP produced higher %VC/syll than M43TD during reading, but the opposite was true during extemporaneous speech. M04CP and M43TD utilized similar LVI during reading, but during extemporaneous speech M04CP's LVI was lower than M43TD. Across tasks, M04CP demonstrated lower LVT and higher LVE than M43TD. During the reading task, M04CP produced a longer inspiratory duration than M43TD, but the opposite was true for extemporaneous speech. This task difference appeared to be due to the fact that M04CP produced the same inspiratory duration for both tasks, but M43TD increased inspiratory duration during the extemporaneous speech task.

Task comparisons. M04CP and M43TD responded to changes in tasks in the same manner for the majority of speech production and speech breathing variables. Both subjects decreased utterance length and speech rate, increased LVI and LVT and decreased LVE. The only differences in task patterns were for intensity, %VC/syll, and inspiratory duration.

Pair 4: M08CP and M75TD

M08CP: Reading vs. Extemporaneous Speech

M08CP was a 13-year-old male with spastic, quadriplegic cerebral palsy, concomitant speech motor involvement, and no language impairment. M08CP produced approximately the same utterance length (MD = 0.03 syll) at approximately the same speaking rate (MD = 0.03 syll/sec) across both tasks. He maintained approximately the same intensity (MD = 82dB) across tasks, so the lung volume changes discussed below were not driven by change in intensity but rather were the likely product of task differences. M08CP demonstrated higher LVI, LVT, and LVE, lower %VC/syll, and longer inspiratory duration in extemporaneous speech than in reading.

M75TD: Reading vs. Extemporaneous Speech

M75TD was a 13-year-old typically developing male. M75TD produced shorter utterances (MD = 1.54 syll) in extemporaneous speech than in reading. This difference in utterance length was likely due to his slower rate in the extemporaneous speech task than in reading (MD = 1.39 syll/sec). M75TD demonstrated higher LVI, LVT, LVE, %VC/syll, and longer inspiratory duration during extemporaneous than during reading.

Comparison of M08CP to M75TD

Participant comparisons. Across tasks, M08CP demonstrated differences in speech production and speech breathing behavior as compared to M75TD. M08CP produced shorter utterances, slower speech rate, lower LVT, higher LVE, higher %VC/syll, and shorter inspiratory duration. Differences in LVI between subjects appeared to be mediated by task. M08CP demonstrated lower LVI in reading, but higher LVI in extemporaneous speech. The only similarity was SPL.

Task comparisons. M08CP and M75TD responded to changes in tasks in the same manner for the majority of speech production and speech breathing variables. Both subjects decreased utterance length, maintained intensity, increased LVI and LVT and produced longer inspiratory durations in extemporaneous speech. The only differences in task patterns were for speech rate, LVE, and %VC/syll.

Discussion

This study sought to investigate speech breathing performance in two different connected speech tasks, reading and extemporaneous speech, in children with CP. Age- and sex-matched typical peers were included as a means of comparison given that there are limited data regarding speech breathing behavior, particularly as it related to task differences, in TD children. Two major themes emerged from the data: 1) Children with CP, particularly those with concomitant speech motor involvement, demonstrate different speech production and speech breathing patterns than TD peers and 2) Speech task impacts speech production and speech breathing variables in both children with CP and TD peers, but the extemporaneous speech task did not seem to exaggerate group differences.

Theme #1: Children with CP Are Different from TD Children

Children with CP demonstrate differences in speech production and speech breathing variables. However, the patterns of difference between children with CP and TD children appear to depend on speech motor involvement status. Thus, this we will discuss our results for the two children with CP and speech motor involvement separately from the two children with CP and no speech motor involvement.

Prior to the discussion of the children with CP, it is important to place the data from our TD children in context of previously published literature. To our knowledge, only one study has examined similar speech breathing variables in reading and extemporaneous speech in TD children of approximately the same age (Hoit et al., 1990). Data from the TD children in our study were similar to that of the 10- to 16-year-old TD children presented in Hoit et al. (1990) though the range of values was often wider for our study, particularly for the extemporaneous speech task. For example, the range of LVI during the reading and extemporaneous speech tasks in Hoit et al. (1990) was 6.21%VC – 17.13%VC and 6.04%VC – 18.46%VC, respectively[1], whereas the range of values for the TD children in our study was 8.30%VC – 17.08%VC and 2.06%VC – 20.45%VC, respectively. The primary difference between the two studies was utterance length. The range of utterance length for the reading and extemporaneous speech tasks in Hoit et al. (1990) was 9.08 – 11.68 syllables and 8.78 – 11.86, respectively. The range of utterance length for the reading and extemporaneous speech tasks in our study was 9.05 – 15.54 utterance and 7.41 – 22.55 syllables, respectively. This resulted in a difference in %VC/syll such that the values from our study were smaller than those presented in Hoit et al. (1990). The wider range of lung volume values and differences in utterance length were likely due to methodological differences. Measurements were only taken from the first 10 utterances of the extemporaneous speech task in Hoit et al. (1990) as opposed to the entire task. The TD children in our study produced between 26 and 41 utterances during the extemporaneous speech task. It is no surprise that by doubling, tripling, or even quadrupling the amount of available data the range of values would become wider. Further, the data from Hoit et al. (1990) represent mean data from 10 children per age. If individual data were presented, they likely would have depicted a wider range of values.

The similarities in the TD data from our study and Hoit et al. (1990) allow us to use the magnitude of difference in statistically significant comparisons from Hoit et al. (1990) as a benchmark with which to evaluate our lung volume data. The magnitude of difference in significant LVI and LVT comparisons ranged from 5-10%VC and the magnitude of difference in significant LVE comparisons was approximately 3%VC. Approximately 80% of lung volume

[1] Values from Hoit et al. (1990) reported here were transformed, such that %VC was relative to an end expiratory level set at 0%VC. This was done by subtracting 35%VC from all reported values as 35%VC was the reported end expiratory level of that study.

comparisons between children with CP and speech motor involvement and their age- and sex-matched TD peer reached or exceeded these thresholds. This same is true for approximately 50% of lung volume comparisons between children with CP and no speech motor involvement and their age- and sex-matched TD peer.

Children with CP and speech motor involvement. The two children with CP and speech motor involvement in our study were F01CP and M08CP. For the speech production variables, both of these subjects produced shorter utterances, slower speech rate, and equivalent intensity as compared to their TD peer. These results held true across both tasks. While reduced utterance length has been discussed as a common auditory-perceptual characteristic of children with CP and speech motor involvement (Workinger & Kent, 1991), this is the first objective data documenting the phenomenon. Slow speech rate has been consistently observed in the CP population (Hodge & Gotzke, 2014; Hustad et al., 2010, 2019; Wolfe, 1950; Workinger & Kent, 1991). Auditory-perceptual studies regarding loudness in children with CP have reported mixed results, with some children being described as excessively loud, some as too quiet, and some as monoloud (Rutherford, 1944; Workinger & Kent, 1991). There has not been a large-scale objective analysis of intensity in children with CP, so it is difficult to fit our subjects within the broader picture of the CP population. However, our data indicate that not all children with CP have challenges regulating intensity during speech production.

For speech breathing variables, both F01CP and M08CP utilized lung volumes that likely required greater active muscle forces during speech production than their TD peer. However, their speech breathing patterns were not identical. During the reading task, F01CP initiated and terminated speech below end expiratory level meaning that she had to exclusively rely on active muscle forces throughout her utterance to support speech production. Similarly, during extemporaneous speech, F01CP began her utterances above but close to end expiratory level and terminated her utterances below end expiratory level. The complete reliance on active muscle forces, particularly at the ends of utterances, could explain why F01CP demonstrated reductions in LVE as compared to her typical peer in that F01CP could just not physically support a wider range of lung volumes. M08CP, on the other hand, was generally able to initiate speech at an appropriate lung volume level to take advantage of passive recoil forces, but terminated speech at or below end expiratory level requiring greater utilization of active muscle forces than his typical peer at the ends of utterances. This behavior was likely due, in part, to M08CP's greatly increased %VC/syll. M08CP "lost" lung volume at a much more rapid pace which required him to terminate speech at lower lung volumes. These data support previous findings of increased respiratory muscle activity during speech production in children with CP as compared to TD children (Clair-Auger et al., 2015; Edgson et al., 2021). Speech production is likely very fatiguing for both of these children.

Speech motor involvement is the result of physiologic deficits (e.g., weakness, incoordination) in any single or combination of speech subsystems. These data support the prevailing wisdom that children with CP often demonstrate deficits across multiple speech subsystems (Allison & Hustad, 2018a, 2018a; Hodge & Wellman, 1999; Workinger & Kent, 1991). Speech rate and utterance length are influenced by coordination and timing at all subsystem levels, particularly the articulatory and respiratory subsystems. For example, respiratory impairment (e.g., smaller LVE) and/or articulatory impairment (e.g., slowed speech rate) may lead to reduced utterance length because the individual must stop to breathe regardless of how many syllables have been produced when they run out of pressure to generate speech. Lung volume measures are primarily influenced by the coordination and timing of the respiratory and laryngeal subsystems. For example, higher %VC/syll during speech production is indicative of more lung volume being “lost” through the vocal tract than is typical. The most likely place to “lose” air is at the level of the larynx. This could indicate that the vocal folds do not close properly during vibration or that the coupling between the laryngeal and respiratory subsystems is not as tightly coordinated.

While both of these children likely demonstrate multiple speech subsystem deficits, the resulting speech production patterns indicate different impairment profiles. Identifying subgroups of children with CP based on similar speech impairment profiles is an emerging area of research (Allison & Hustad, 2018b; Hustad et al., 2010). Thus far, the research in this area has focused on acoustic and auditory-perceptual measures. This study provides evidence that respiratory kinematic measures may aide in the development of these profile groups. This study also provides evidence that respiratory subsystem impairment cannot be diagnosed based on speech intelligibility measures and auditory-perceptual features alone. F01CP almost exclusively relies on active muscle forces during speech production, but was highly intelligible and demonstrated minimal signs of respiratory and/or laryngeal subsystem impairment (e.g., occasional breathy voice and loudness decay). It was not until the examination of her speech breathing patterns that one could truly appreciate how fatiguing speech production likely was for her. This type of profile (e.g., speech breathing impairment despite high intelligibility and very mild speech motor involvement) was also observed in Edgson et al. (2021). Fatigue is a major contributor to communicative participation (Yorkston et al., 2001) and should be discussed during assessment and treatment planning regardless of how “mild” the speech motor involvement appears.

Children with CP and no speech motor involvement. The two children with CP and no speech motor involvement in our study were F02CP and M04CP. While there were some mean differences between these children and their TD peers, values for a majority of speech production and speech breathing variables fell within a more typical range (based on the mean values of TD children in this study). In fact, in some cases the children with CP outperformed their TD peers. For example, both children with CP produced longer utterances than their TD peers and F02CP utilized lung volumes that were able to capitalize on passive recoil forces for the majority of the utterance as opposed to F38TD who consistently terminated speech very close to or below EEL. The major consistent difference was a longer inspiratory duration for the children with CP than their TD peers. Since neither of these children with CP had language impairment and both produced longer utterances, it is likely that the longer inspiratory duration was the product of planning language for longer utterances. Given that there were only two children with CP and no speech motor involvement, it is too early to conclude that these children do not demonstrate any speech breathing differences when compared to TD peers. It is necessary to conduct a thorough investigation of speech breathing variables in a large sample of children with CP and no speech motor involvement before making any definitive conclusions.

Theme #2: Speech Task Matters

While individual variation exists, it is clear from our data that task affects how the individual uses the respiratory system to support speech production. The majority of children (CP and TD) demonstrated longer utterances, slower speech rate, higher LVI, LVT, LVE, and %VC/syll, and longer inspiratory duration in extemporaneous speech as compared to reading. Intensity was relatively unchanged across tasks, so any change in lung volume was not related to changes in intensity. Additionally, the extemporaneous speech task did not appear to exacerbate differences between children with CP and their TD peers as the magnitude of the difference for each variable was similar across tasks. Though preliminary due to our sample size, these data are consistent with findings regarding task effects in similar speech production and speech breathing variables from TD children and healthy adults. Speech rate is slower in tasks requiring more language formulation, like extemporaneous speech, in TD children and healthy adults (Haselager et al., 1991; Huber & Darling, 2011; Logan et al., 2011; Mitchell et al., 1996; Nip & Green, 2013). Healthy young adult women produced shorter utterances and higher %VC/syll in an extemporaneous speech task as compared to a speech task in which an outline was provided (Mitchell et al., 1996). Typically aging adults demonstrated higher LVI, LVT, and %VC/syll in extemporaneous speech as compared to reading (Huber & Darling, 2011). Statistical tests for task comparisons were not conducted in Hoit et al. (1990). However, some similar trends are noted across studies when examining mean data reported for each task in Hoit et al. (1990). Similar to our study, LVE and %VC/syll were higher and LVI was either the same or higher for extemporaneous speech as compared to reading in Hoit et al. (1990).

Our data provide further evidence that the cognitive-linguistic demands of a particular speech task impact speech production and speech breathing variables. The task effects are likely due to the increased cognitive-linguistic demands of the extemporaneous speech task. During a reading task, the content is already provided, so the individual does not have to allocate cognitive-linguistic resources to planning the language of the upcoming utterance. Instead, the speaker can plan for how much lung volume to use and when to adduct or abduct the vocal folds. During extemporaneous speech, the speaker must plan the language of the upcoming utterance. If there is little guidance given regarding the content of the message that is being generated, as in an extemporaneous speech task, then language planning must occur simultaneously with speech production. Shorter utterances, slower speech rate, and longer inspiratory duration may reflect this necessary planning behavior. Since the speaker does not have a specific plan for their utterance, it is likely harder to plan where to breathe in regard to syntax. Pausing, particularly breath pausing, at locations related to syntax is critical to successful communication (Darling-White & Huber, 2020; Grosjean & Collins, 1979; Huber et al., 2012; Price et al., 1991; Shah et al., 2006; Winkworth et al., 1994). Thus, speech may be initiated at higher lung volumes in an effort to ensure breath pausing occurs at a syntactic boundary rather than being forced to breathe at a location unrelated to syntax due to respiratory physiologic constraints. The coordination of the laryngeal and respiratory subsystems is also less tightly regulated, potentially leading to higher %VC/syll, in extemporaneous speech than in reading due to the redistribution of cognitive-linguistic resources to language planning over the speech motor plan.

Limitations and Future Research

Future work must include a larger sample of children with CP and their TD peers. These data are highly preliminary. A larger sample would allow for further examination of the impact of speech motor involvement and cognitive-linguistic impairment on speech production and speech breathing variables. A larger sample could also include children with CP with different types of tonal abnormalities. In the present study, all the children with CP presented with spastic type CP. This is the most commonly occurring type, but it is not the only type. Future studies should include children with athetoid (dyskinetic) and ataxic subtypes to determine if speech breathing is affected differently across the subtypes.

The present study only examined two different types of speech tasks, reading and extemporaneous speech. In the future, it might be interesting to examine how speech breathing changes in tasks such as story retelling or conversation. This would allow a wider range of children to participate given that not all children with CP are able to read due to cognitive-linguistic deficits. A wider range of speech tasks would also be more representative of the types of speech production demands children are required to do in daily life.

Conclusions

This study is the first to examine speech breathing data in reading and extemporaneous speech tasks in children with CP. Similar to studies using single sentence production (Clair-Auger et al., 2015; Edgson et al., 2021), our data indicate that children with CP and speech motor involvement demonstrate patterns of speech breathing behavior that are indicative of an overreliance on active muscle forces during speech production. This can occur even when traditional signs of respiratory subsystem impairment are lacking (e.g., highly intelligible and few auditory-perceptual features). Further, different patterns of physiologic impairment can result in an overreliance on active muscle forces during speech production. However, this does not appear be the case for children with CP and no speech motor involvement. This study also examined the impact of task on speech production and speech breathing behavior in children with CP and their TD peers. Both children with CP regardless of speech motor involvement and their TD peers alter speech production and speech breathing behavior based on the type of connected speech task being produced. Though preliminary, these data do support previous work in TD children and typical adults (Haselager et al., 1991; Huber & Darling, 2011; Logan et al., 2011; Mitchell et al., 1996; Nip & Green, 2013) strengthening the idea that the speech motor and cognitive-linguistic systems interact during speech production and the respiratory subsystem is an excellent way to view these interactions. Based on these data, assessments designed to diagnosis and create intervention plans for children with motor speech disorders must include several types of connected speech tasks, not only to maintain ecological validity but to determine the impact of cognitive-linguistic demands on speech motor behavior. These data will serve as the foundation for future work examining speech breathing in children with CP and the development of interventions to specifically target speech breathing impairment in children with CP.

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Figure 1: Lung volume for each pair. End expiratory level is represented as 0%VC on the vertical axis. For each bar, lung volume initiation is the highest point, lung volume termination is the lowest point, and the shaded area is lung volume excursion. Lines represent standard errors of lung volume initiations and terminations. (a) F01CP and F17TD. (b) F02CP and F38TD. (c) M04CP and M43TD. (d) M08CP and M75TD.

a. c.

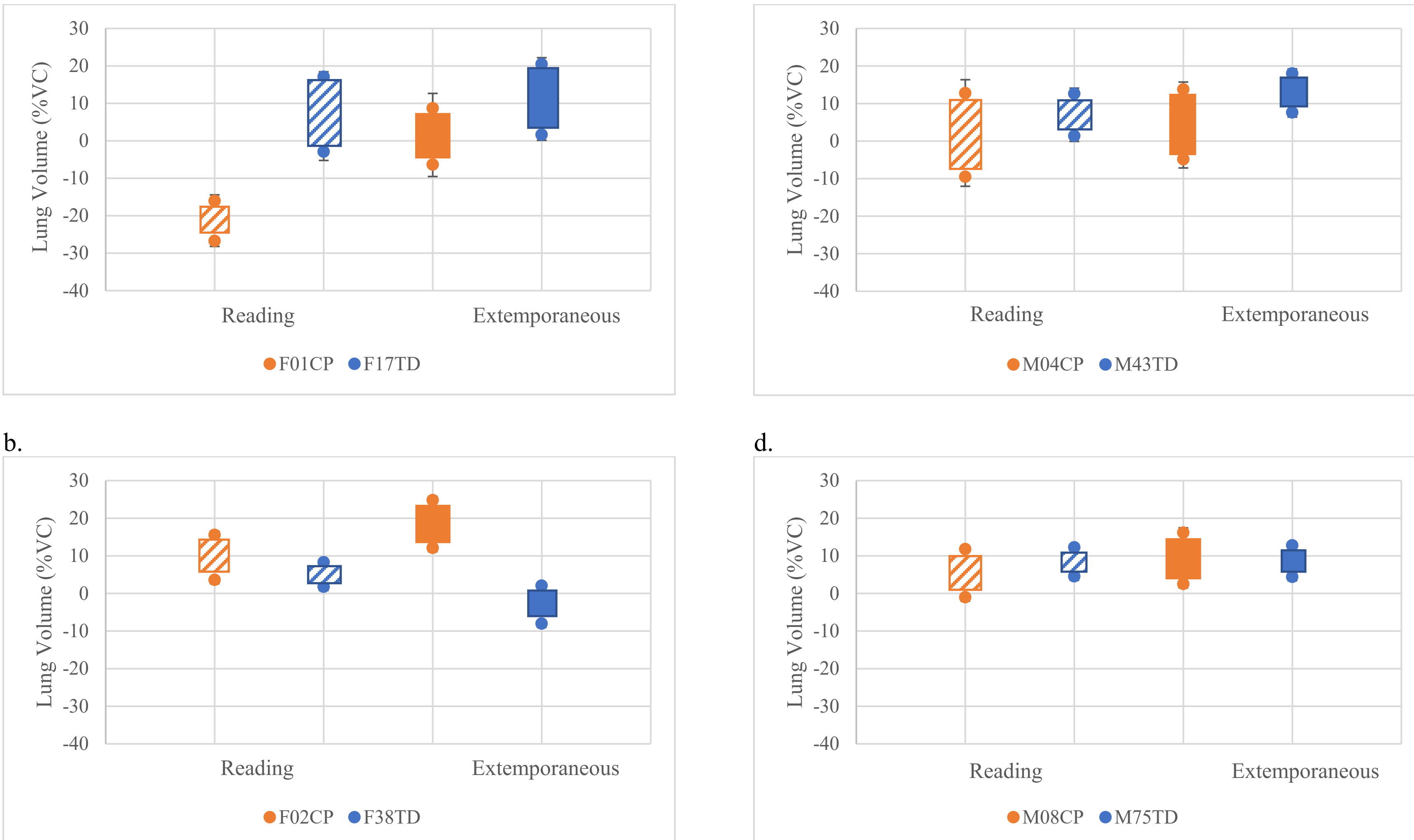

Table 1: Demographics for children with cerebral palsy.

Participant	**Age (years;months)**	**Speech motor involvement**	**Intelligibility**	**Primary speech characteristics**	**Language impairment**	**Type of CP**	**GMFCS**
F01CP	13;5	Yes – Mild	91%	Imprecise articulation, occasional breathy voice, occasional loudness decay	Severe impairment	Spastic diplegia	II
F02CP	14;6	No	96%	n/a	No impairment	Spastic hemiplegia	I
M04CP	11;9	No	93%	n/a	No impairment	Spastic	I
M08CP	13;8	Yes - Moderate	70%	Slow rate, short phrases, loudness decay, hypernasality, imprecise articulation, inappropriate silences, occasional strained voice	Did not complete	Spastic quadriplegia	II

Note. M04CP did not report the topographical distribution of their spasticity. F=female; M=male; CP=cerebral palsy; GMFCS=Gross Motor Function Classification System

Table 2: Descriptive Results for Pair 1

Participant	**# of Utterances**	**Utterance Length (syll)**	**Speech Rate (syll/sec)**	**SPL (dB)**	**%VC/syll**	**%LVI (%VC)**	**%LVT (%VC)**	**%LVE (%VC)**	**Inspiratory Duration (sec)**
F01CP read	25	9.92(0.89)	3.35(0.11)	77.13(0.43)	1.10(0.08)	-16.06(1.63)	-26.73(1.48)	10.67(0.99)	0.74(0.07)
F01CP ex	18	6.83(1.01)	3.29(0.21)	77.04(0.68)	2.32(0.31)	8.69(3.97)	-6.34(3.19)	15.02(2.41)	0.88(0.06)
F17TD read	11	22.55(3.09)	4.94(0.25)	78.60(0.45)	0.82(0.10)	17.08(1.36)	-2.92(2.32)	20.00(3.03)	0.55(0.04)
F17TD ex	26	15.54(1.77)	4.03(0.23)	77.10(0.32)	1.55(0.22)	20.45(1.74)	1.64(1.50)	18.81(1.65)	0.81(0.08)

Note. Descriptive results include means and standard errors in parentheses. CP=cerebral palsy; TD=typically developing; read=reading task; ex=extemporaneous task; syll = syllables; SPL = sound pressure level; VC/syll = vital capacity per syllable; LVI = lung volume initiation; LVT = lung volume termination; LVE = lung volume excursion.

Table 3: Descriptive Results for Pair 2

Participant	# of Utterances	Utterance Length (syll)	Speech Rate (syll/sec)	SPL (dB)	%VC/syll	%LVI (%VC)	%LVT (%VC)	%LVE (%VC)	Inspiratory duration (sec)
F02CP read	19	13.55(1.41)	4.98(0.22)	78.42 (0.46)	0.89(0.03)	15.57(0.97)	3.60(0.91)	11.97(1.29)	0.47(0.04)
F02CP ex	27	10.19(1.02)	3.14(0.23)	77.36 (0.43)	1.59(0.25)	24.81(0.98)	12.12(1.00)	12.69(1.02)	0.69(0.06)
F38TD read	33	7.41(0.57)	4.85(0.21)	84.82 (0.29)	0.93(0.08)	8.30(0.52)	1.78(0.61)	6.52(0.67)	0.28(0.02)
F38TD ex	41	11.00(1.24)	4.05(0.23)	80.44(0.27)	1.25(0.13)	2.06(0.58)	-8.04(0.98)	10.10(0.91)	0.46(0.03)

Note. Descriptive results include means and standard errors in parentheses. CP=cerebral palsy; TD=typically developing; read=reading task; ex=extemporaneous task; syll = syllables; SPL = sound pressure level; VC/syll = vital capacity per syllable; LVI = lung volume initiation; LVT = lung volume termination; LVE = lung volume excursion.

Table 4: Descriptive Results for Pair 3

Participant	# of Utterances	Utterance Length (syll)	Speech Rate (syll/sec)	SPL (dB)	%VC/syll	%LVI (%VC)	%LVT (%VC)	%LVE (%VC)	Inspiratory duration (sec)
M04CP read	13	20.23(2.15)	4.53(0.23)	78.05 (0.36)	1.11(0.10)	12.76(3.60)	-9.54(2.50)	22.30(2.92)	0.60(0.16)
M04CP ex	24	19.04(1.93)	3.67(0.18)	80.92 (0.32)	0.90(0.08)	13.77(1.97)	-4.86(2.29)	18.63(2.23)	0.63(0.04)
M43TD read	22	11.14(1.10)	3.88(0.23)	79.37 (0.42)	1.01(0.12)	12.65(1.45)	1.38(1.46)	11.27(1.48)	0.51(0.06)
M43TD ex	37	9.05(1.07)	3.45(0.17)	79.16(0.19)	1.23(0.13)	18.00(1.22)	7.63(1.23)	10.37(1.28)	0.75(0.07)

Note. Descriptive results include means and standard errors in parentheses. CP=cerebral palsy; TD=typically developing; read=reading task; ex=extemporaneous task; syll = syllables; SPL = sound pressure level; VC/syll = vital capacity per syllable; LVI = lung volume initiation; LVT = lung volume termination; LVE = lung volume excursion.

Table 5: Descriptive Results for Pair 4

Participant	# of Utterances	Utterance Length (syll)	Speech Rate (syll/sec)	SPL (dB)	%VC/syll	%LVI (%VC)	%LVT (%VC)	%LVE (%VC)	Inspiratory duration (sec)
M08CP read	67	4.90(0.29)	2.26(0.06)	81.43(0.27)	3.41(0.34)	11.78(0.56)	-1.02(0.71)	12.81(0.74)	0.39(0.02)
M08CP ex	49	4.78(0.43)	2.24(0.10)	82.25(0.25)	2.72(0.32)	16.16(1.28)	2.49(1.48)	13.67(1.48)	0.50(0.03)
M75TD read	18	14.06(1.61)	4.98(0.16)	82.73(0.53)	0.58(0.05)	12.25(0.86)	4.54(0.99)	7.71(0.97)	0.58(0.08)
M75TD ex	31	12.52(1.64)	3.59(0.21)	82.00(0.35)	0.85(0.11)	12.76(0.79)	4.38(0.94)	8.38(1.02)	0.79(0.05)

Note. Descriptive results include means and standard errors in parentheses. CP=cerebral palsy; TD=typically developing; read=reading task; ex=extemporaneous task; syll = syllables; SPL = sound pressure level; VC/syll = vital capacity per syllable; LVI = lung volume initiation; LVT = lung volume termination; LVE = lung volume excursion.

Table 6: Summary of Participant Comparisons

Participant	Utterance Length (syll)	Speech Rate (syll/sec)	SPL (dB)	%VC/syll	%LVI (%VC)	%LVT (%VC)	%LVE (%VC)	Inspiratory Duration (sec)
F01CP read	-	-	=	+	-	-	-	+
F01CP ex	-	-	=	+	-	-	-	+
F02CP read	+	+	-	-	+	+	+	+
F02CP ex	-	-	-	+	+	+	+	+
M04CP read	+	+	=	+	=	-	+	+
M04CP ex	+	+	=	-	-	-	+	-
M08CP read	-	-	=	+	-	-	+	-
M08CP ex	-	-	=	+	+	-	+	-

Note. CP=cerebral palsy; read=reading task; ex=extemporaneous task; syll = syllables; SPL = sound pressure level; VC/syll = vital capacity per syllable; LVI = lung volume initiation; LVT = lung volume termination; LVE = lung volume excursion.; + means the value was higher than the age- and sex-matched peer; - means the value was lower than the age- and sex-matched peer; = means the value was approximately the same as the age- and sex-matched peer.