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The Effects of Changes in Vocal Loudness on Measures of Speech Physiology in Children with Cerebral Palsy and Typically Developing Children

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The undersigned certify that they have read and recommend to the Faculty of Arts for acceptance, a thesis entitled The Effects of Changes in Vocal Loudness on Measures of Speech Physiology in Children with Cerebral Palsy and Typically Developing Children, submitted by Meghan Edgson in partial fulfillment of the requirements for the degree of Bachelor of Arts.

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ABSTRACT

Cerebral palsy (CP) is a neurodevelopmental disorder that can involve the speech motor control in a large percentage of those having the disorder. This study aims to describe respiratory and laryngeal subsystems involved in speech motor control in children with CP by investigating one of the techniques that targets healthy vocal loudness levels.

Eight English-speaking children, four with CP and four without, were prompted to repeat sentences and produce maximum phonation duration. Children were cued to adjust their vocal loudness levels to perceived conversational, half conversational, twice conversational, and four times conversational loudness. Participants repeated a sentence five times under all perceived loudness conditions. Participants also produced three maximum phonation duration under conversational loudness and perceived twice conversational loudness conditions. The speech data were analyzed for intercostal-oblique intermuscular coherence, fundamental frequency (F0) mean, vowel duration, and vowel space.

The results indicate that intercostal-oblique intermuscular coherence visually changed across tasks in both participant groups, especially in the older participants. F0 average and vowel duration increased with increased perceived vocal loudness in the control group, but only F0 average changed with loudness in the group with CP. Vowel space became more peripheral in both groups with increased perceived loudness. Based on these results, young children may make loudness adjustments by increasing chest wall muscular activity and neuromuscular drive to the chest wall. All children seem to make different degrees of laryngeal adjustments to increase loudness levels during speech, as evidenced by significant acoustic changes. This paper provides a descriptive analysis of intermuscular coherence and speech acoustics in children, which serves

as a baseline for speech therapies that can lead to biomechanical and neuromuscular efficiency in the speech of children with CP.

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CHAPTER I. Introduction

1.0. Cerebral palsy and development

Cerebral palsy (CP) is a lifelong neurodevelopmental disorder that results from brain disturbances before or during infancy, occurring in two of every 1000 live births (Odding et al., 2005; Oskoui et al., 2013; Rosenbaum, 2006). As many as 80% of individuals with CP have impaired speech. The most common motor speech disorder among this population is dysarthria (Parisi et al., 2016). Dysarthria, secondary to CP, includes deficits in breath control, speech rate, pitch and loudness variability, acoustic contrasts, the production of speech sounds (e.g. plosives, fricatives, and affricates), formant transitions, and intelligibility (Patel, 2002; Wit et al., 1993). As CP is a disorder that continues across the lifespan, it is essential to find therapeutic techniques that are suitable for all ages and cognitive levels. It is also important to consider CP in terms of a developmental framework. Individuals with neurodevelopmental disorders may not transition well from healthcare in childhood and adolescence into healthcare in adulthood. Thus, it is important to find ways for individuals with CP to have smooth transitions for receiving healthcare including rehabilitation from childhood through adulthood (Binks et al., 2007; Singh et al., 2010; Singh & Tuomainen, 2015).

There are developmental changes in laryngeal and respiratory structure and function from childhood to adulthood caused by changes in laryngeal size, vibratory patterns of the vocal folds, size and compliance of the lungs and airways, as well as compliance of the chest wall (Stathopoulos & Sapienza, 1997). For example, airway resistance and compliance decrease with age because of increases in airway diameter and changes in the elasticity of respiratory tissues. This leads to a greater contribution of the rib cage during speech in children, as well as higher tracheal pressures compared to those observed in adults. In addition, children have lower vocal efficiency levels than do adults (Tang & Stathopulos, 1994). The present case study investigates children from the ages of eight to twelve years thus, these developmental trends may play a role in the neuromuscular and acoustic measures of speech. We know that typically developing children make measurably different speech breathing and laryngeal adjustments when changing speech loudness. This study adds to this knowledge by describing how children with CP make loudness adjustments in the context of neuromuscular difficulties.

1.1 Intermuscular coherence

A variable called intermuscular coherence can be used to describe the relationship between two muscle groups (i.e., intercostal and oblique muscles of the chest wall). Intermuscular coherence is a cross-correlation, bound between zero and one, of two muscles' electrical activity, which is detectable when the muscles contract (Grosse et al., 2002). This safe and non-invasive measure can tell us about descending motor pathways, their control, and the coordination of specific muscle groups (Boonstra, 2013). Specifically, intermuscular coherence measures whether two muscles fire similarly within a specified frequency range. The electrical signals used to calculate intermuscular coherence are measured by recording data from the muscle groups of interest using surface electromyography (sEMG), which records activity from surface electrodes over the muscles and produces a record called an electromyogram, or EMG (Grosse et al., 2002; Pinel, 2013). Motor units from different muscles, which are motor neurons and the skeletal muscles they innervate, sometimes fire in the same frequency range (Farmer et al., 1993). This phenomenon led to the idea that some motor units have the same or similar cortical and corticospinal inputs, or drives, at specific ranges of muscle firing frequencies. This means that when there is a high intermuscular coherence between two muscles, similar brain or spinal cord regions may be controlling them both. Thus, intermuscular coherence is used to infer neuromodulation of muscles during motor tasks by measuring how well skeletal muscles work together. Moreover, intermuscular coherence can quantify the extent of motor rehabilitation in individuals with brain or spinal cord injuries (Farmer et al. 1993; Fisher et al., 2012; Norton & Gorassini, 2006).

Additionally, intermuscular coherence is used to measure improvements in breath control after vocal loudness manipulation in children with dysarthria secondary to CP (Mager, 2015). Given that CP is characterized by motor speech deficits, it is essential to look at neuromuscular coordination of the chest wall muscles in children with this neurodevelopmental disorder through measuring intercostal-oblique intermuscular coherence. In the present study, intercostal-oblique intermuscular coherence is analyzed in the medium frequency bandwidth (beta and gamma), as signals from this bandwidth are known to originate from the motor cortex (Grosse et al., 2002). It will be used as a measurement of cortico-muscular adaptation to changes in vocal loudness levels.

1.2 Speech acoustics

Sound pressure level (SPL) and its perceptual correlate, vocal loudness, are also used to describe motor speech disorders. SPL is a logarithmic scale that quantifies sound pressures perceivable by humans and is measured in decibels (dB). One way that vocal loudness is increased is through the maximization of subglottal pressure, or pressure that builds up underneath the vocal folds. The internal intercostal and oblique muscles are involved in maintaining a constant tracheal pressure against a decreasing lung volume during conversational speaking and also are involved in increasing tracheal pressures associated with loud speech. These muscle groups are activated during speech, especially when it is loud (Hoit et al., 1988). Therefore, investigation into how the intercostal and oblique muscles work together to facilitate speech, as well as understanding neuromodulation, is essential in describing motor speech disorders. In addition, the vocal folds must increase their tension to accommodate for the increases in pressure. This adjustment is done by the laryngeal muscles. Thus, acoustic measures warrant investigation as well.

Voluntary increases of vocal loudness lead to increases in SPL; fundamental frequency (F0, the lowest frequency of a complex wave and the rate at which the vocal folds vibrate); utterance duration; final-word lengthening; F0 variation (the standard deviation of F0); formant frequencies; and F0 declination (the difference between F0 at the beginning and at the end of an utterance)(Dromey & Ramig, 1998; Huber et al. 1999; Watson & Hughes, 2006). These acoustic variables may reflect intelligibility and they also may be deficient in some individuals with dysarthria secondary to CP (Patel, 2002).

However, it is important to note that the studies cited above, Dromey & Ramig (1998) and Watson & Hughes (2006), both involve loudness manipulation and acoustic variables in healthy adult participants. Stathopoulos & Sapienza (1997) found that children modulate loudness differently than adults, producing loud speech with higher F0 and higher tracheal pressures. The next step is to investigate how loudness modulations are made in children with neuromuscular disorders. In addition, it may not be appropriate to compare children with CP to healthy individuals, nor to use healthy individual productions as treatment targets. “Typical speech” does not necessarily have to be the goal for children with CP, and there are possible alternative paths to functional communication (e.g. Patel, 2002; Rosenbaum, 2006). Additionally, even among healthy speakers, individuals vary in the phonetic and articulatory adjustments made to attain clear speech (Hazan & Markham, 2004). Thus, any comparison between results found in children with CP and in typically-developing children should be analyzed with these limitations in mind.

Some research shows that at certain loudness levels (i.e. shouting), speech becomes less intelligible in healthy adults (Dreher & O'Niell, 1957; Rostolland, 1982). However, the present study targets healthy vocal loudness levels rather than extreme loudness. Lastly, loudness manipulation could be an intervention technique that is appropriate across the lifespan, which is important as CP is a non-progressive disorder that persists into adulthood (Rosenbaum, 2006). In sum, the acoustic measures of vowel duration, average F0, and formant values (F1 and F2) are used in this study as measurements of adjustment made to produce loud speech.

1.3 Guiding literature

One study investigated intercostal-oblique intermuscular coherence, acoustic properties, and vocal intensity with speech production in healthy adults as well as children. Tam (2017) tested healthy adults and typically developing children in a single session using speech tasks such as sentence repetition and sustained maximum phonations produced at two different vocal loudness levels (conversational loudness and twice conversational loudness). The results showed that sound pressure level and average F0 increased as a result of voluntary or automatic (as a result of listening to noise) loudness increases, but intercostal-oblique intermuscular coherence remained constant across conditions. Tam (2017) inferred that in individuals, cortical drive to the intercostal and oblique muscles was stable across loudness levels, but laryngeal adjustments during loud speech were observed. However, these results may not reflect the changes in intermuscular coherence that occur with voluntary loudness manipulation in children with motor speech disorders. It is possible that children with CP may display increased intercostal-oblique intermuscular coherence as well as altered acoustic properties within a single session of increased vocal loudness. This result would be consistent with previous findings that within a single session, vocal loudness cues led to increases intercostal and oblique muscle activity, utterance durations, F0, and vocal intensity in children with CP (Archibald, 2011; Levy et al. 2017). Alternatively, children with CP might need more intensive bouts of vocal loudness training to see significant effects. Either way, intermuscular coherence and acoustic results from one session of typically-developing children and children with CP increasing their vocal loudness would provide a baseline for future rehabilitation and therapy techniques aimed towards children with dysarthria secondary to CP. Thus, it is important to figure out what happens to intercostal-oblique intermuscular coherence and speech acoustics in typically-developing children and children with CP when cued to increase vocal loudness, and as a result, respiratory effort.

The purpose of this study is to describe the speech of four children with CP and four typically developing children in terms of intercostal-oblique intermuscular coherence, vocal F0, vowel duration, and formant frequencies at four perceived vocal loudness levels. The outcomes will guide future research on healthy vocal loudness in children with dysarthria and CP and will provide a reference point for future efficient intervention and rehabilitation techniques in treating children with dysarthria.

1.4 Hypotheses

The hypotheses are: i) Intercostal-oblique intermuscular coherence, average F0, and vowel duration will increase and vowels' formant values will become more peripheral with increased perceived vocal loudness in both groups. ii) Children with CP will make more neuromuscular adjustments to the chest-wall during loud speech than typically developing children. iii) Typically developing children make more refined laryngeal adjustments during loud speech than children with CP, as indicated by greater acoustic changes in the typically developing group and greater neuromuscular changes in the group with CP.

CHAPTER II. Methods

2.0 Participants

Eight English-speaking children between the ages of eight and twelve years participated in this study. Four participants had CP and dysarthria and four age and gender-matched controls were typically-developing. The descriptions of the children with cerebral palsy are outlined in Table 1. The control participants were from smoke-free households, had normal or corrected-to-normal hearing and vision, had no respiratory infections on the day of the experiment, and had no problems with speech or language. The participants with CP were also from smoke-free households, had normal or corrected-to-normal hearing and vision, and had no respiratory infections on the day of the experiment. Additionally, the children with CP were described as having spastic-type with spastic dysarthria, which ranged from mild to moderate severity. Three of the four participants with CP were described by speech language pathologists as having reduced breath control, pitch variability, and intelligibility.

Table 1: Participants' type and severity of cerebral palsy, and a list of their age- and gender-matched peers.

Participant Code	Age	Gender	Type of dysarthria	Severity of dysarthria	Age- and gender-matched peer
F1001EL	10	Female	Spastic	Mild	F1001CL
F1201EL	12	Female	Spastic	Moderate	F1201CL
M0801EL	8	Male	Spastic	Moderate	M0801CL
M1201EL	12	Male	Spastic	Moderate	M1201CL

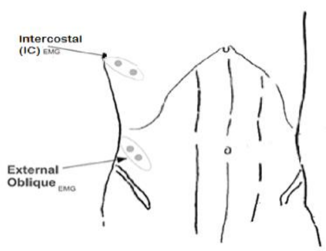
2.1 Equipment

Electromyogram signals were recorded with surface electrodes placed on the participants' skin over their intercostal and oblique muscles. The EMG signals were amplified and bandpass filtered and acquired at a sampling rate of 10 kHz using the Powerlab acquisition system (ADI, Colorado Springs, CO). A small condenser microphone was placed 10 cm from the lips, was amplified and recorded at 44 kHz on DAT tapes for later analysis.

2.2 Procedures and tasks

Participants sat upright in a chair and researchers placed surface electrodes over their intercostal and oblique muscles. Specifically, the electrodes were placed on the right side of each participant's body between the sixth and seventh intercostals, as well as 12-15cm lateral of the body's midline. Figure 1 is a diagram of the electrode placement that was used in this procedure. In addition, a ground electrode was placed on the clavicle to provide a reference point for the EMG signals. The participants performed maximum voluntary contraction tasks to calibrate the EMG signal for each muscle group.

Figure 1: EMG surface electrode placement over the intercostal and oblique muscles (Mager, 2015).



Researchers verbally cued each participant to repeat sentences and sustained maximum phonation durations. First, participants repeated the sentence *I sell a sapapple again* five times at conversational loudness, twice perceived conversational loudness, and four times perceived conversational loudness. Then, participants recalibrated their loudness levels with five repetitions of the sentence at a conversational loudness level, followed by five sentence repetitions at perceived half conversational loudness. Next, participants produced three repetitions of sustained maximum phonation durations (*ah*) at a conversational loudness level and then three repetitions at a twice perceived conversational loudness level.

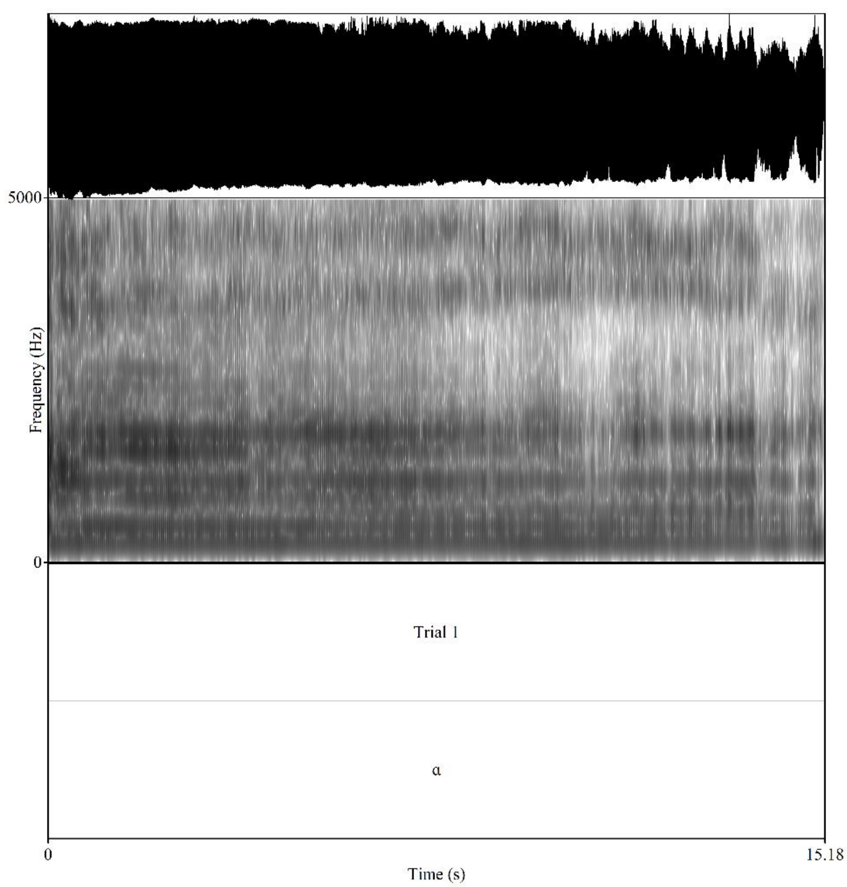
2.3 Analyses

The dependent variables were intercostal-oblique intermuscular coherence, average F0, average vowel duration, and vowel formants. These data were analyzed across perceived loudness levels (conversational loudness, half conversational, twice conversational, and four times conversational) and perceived maximum phonation duration loudness levels (conversational and perceived twice conversational). The recalibration condition data where participants spoke at a conversational loudness level were not analyzed in this study because Archibald (2011) determined that there were no significant differences between the first and second conversational loudness conditions on multiple dependent measures including sound pressure level and F0 for *I* and *sap*. Participant M1201EL was unable to complete maximum phonation durations at perceived twice conversational loudness so there are no data for this participant and task.

Data for the EMG expiratory limbs, which are the expiration portions of breath groups, were segmented with PowerLab software. The expiratory limb was measured using chest wall kinematic signals as a guide. The rib cage and abdomen signals were added together to create a lung volume signal, which was used to detect the expiratory portion of each breath group. Each expiratory limb was measured from the peak of the kinematic waveform to the trough of the waveform. Peak coherence values in the 15-59Hz range were calculated for each participant using MATLAB software and were converted into Fisher's z-scores for statistical analyses.

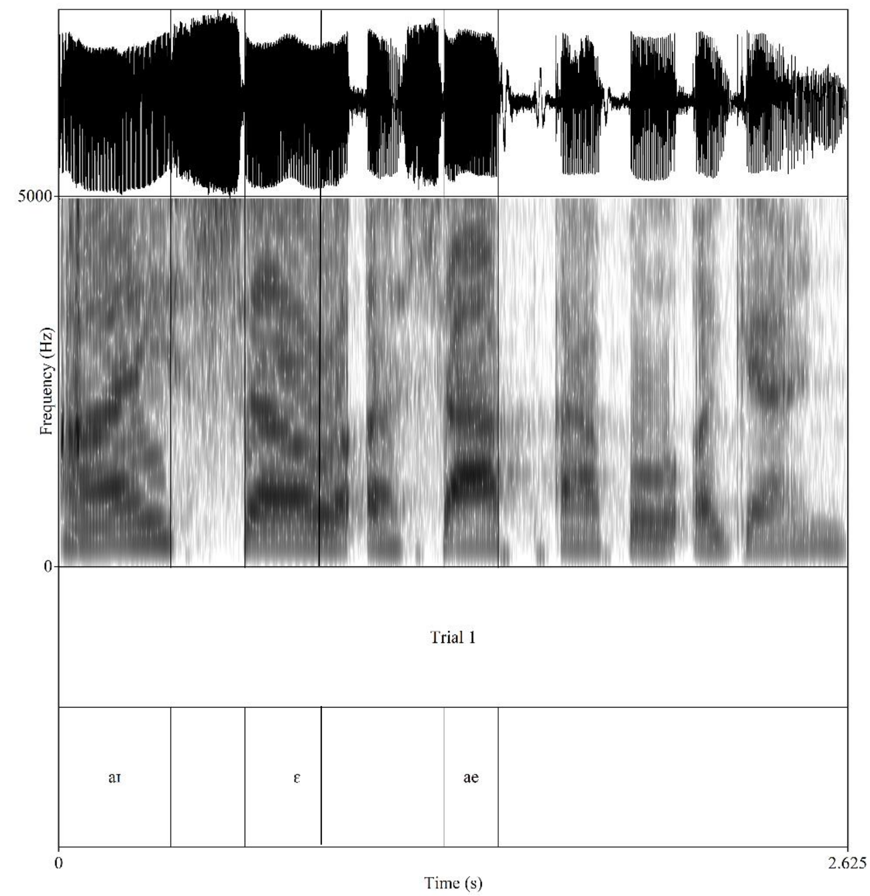
Additionally, the acoustic data were analyzed using Praat software (Boersma, Paul, & Weenink, 2018). As demonstrated in Figure 2 and Figure 3, acoustic data were divided into vowel tiers to measure vowel duration, pitch, and formants. Vowel start- and end-points were determined using the zero crossing nearest the beginning and end of the periodic wave for each vowel. Vowel duration, average F0, and formant values were calculated with a customized Praat script (Dr. B.V. Tucker, University of Alberta, Edmonton, AB). F1 and F2 were measured at 25%, 50%, and 75% of the vowel duration for the vowels /aɪ/, /ɛ/, /æ/ and the sustained maximum phonation durations. All data were compiled into spreadsheets for statistical analysis.

Figure 2: Maximum phonation duration waveform, spectrogram and textgrid in Praat for one typically developing participant.



Zero crossings nearest the beginning and end of the periodic waveform were used to segment the phonation.

Figure 3: Sentence task waveform, spectrogram and textgrid in Praat for one typically developing participant.



Zero crossings nearest the beginning and end of the periodic waveform were used to segment the vowels /aɪ/, /ɛ/, and /æ/.

Data from each individual participant as well as from each group of children were analysed for intercostal-oblique intermuscular coherence, mean and standard deviation of vowel durations, mean and standard deviation of F0, and average formant values. An exploratory One-way ANOVA repeated measures analysis was executed to test for within-subjects differences across perceived loudness levels for intermuscular coherence and acoustic measures in each participant group (Table 3). Additionally, raw coherence values were plotted to investigate visual trends in intercostal-oblique intermuscular coherence for each individual participant and each participant group (Figure 4-Figure 7). Lastly, F0 and vowel durations were analyzed individually for each participant with paired *t*-tests (Table 5 and Table 6). This was done to determine whether F0 and vowel durations at conversational loudness as a baseline changed with increasing perceived vocal loudness for each participant.

CHAPTER III: Results

3.0 Descriptive Statistics

Descriptive statistics for each task and each participant group are outlined in Table 2 for intercostal-oblique intermuscular coherence, vowel duration, and F0. For intermuscular coherence (Table 2A), the CP group appears to have a greater coherence during maximum phonation duration than the control group. During all sentence tasks, the intermuscular coherence is similar between groups. CP group variability for conversational maximum phonation duration is greater than the control group, but for all other conditions there are no notable differences in variability between groups. Intermuscular coherence appears to decrease with increased loudness across tasks in both groups.

Control group maximum phonation duration appear to have greater durations than the CP group (Table 2B). For half-conversational sentences, the CP group seems to have longer vowel durations than the control group on average. In the twice and four-times conversational loudness sentence conditions, the CP group may have similar or longer vowel durations than the control group. Overall, the CP group has more variability in vowel durations than the control group. It appears that maximum phonation durations decrease slightly with increased loudness in both groups. During sentences, vowel durations appear to increase or stay the same with increased loudness. Table 2C outlines the descriptive results for average F0. The CP group looks to have greater F0 than the control group during maximum phonation duration. A similar result is evident for conversational and twice conversational loudness sentences. For half- and four-times-conversational loudness sentences, both groups seem to have similar average F0 values. Overall, the CP group has more variability than the control group, with the exception of conversational maximum phonation duration and four-times conversational loudness sentences, where the variability is comparable between groups. Average F0 appears to increase with loudness across tasks in both groups.

Table 2: Descriptive statistics for intercostal-oblique intermuscular coherence, vowel durations, and F0 in control and CP groups. Group means and standard deviations for intermuscular coherence, vowel duration, and F0, for conversational and perceived twice conversational sustained maximum phonation duration as well as conversational and perceived half, twice, and four times conversational sentences.

A. Intermuscular Coherence

	Max phonations	2X Max phonations	Conversational sentences	0.5X Sentences	2X Sentences	4X Sentences
Control Group Mean	.31	.26	.56	.70	.57	.37
CP Group Mean	.57	.50	.59	.68	.59	.33
Control Group Standard Deviation	.23	.11	.54	.58	.30	.22
CP Group Standard Deviation	.52	.05	.54	.40	.25	.15

B. Vowel Duration in seconds

	Max phonation	2X Max phonation	Conversational sentences	0.5X loud Sentences	2X loud Sentences	4X loud Sentences
Control Group Mean	12.72	10.64	.25	.19	.26	.27
CP Group Mean	5.71	7.89	.33	.35	.33	.35
Control Group Standard Deviation	5.64	3.88	.04	.03	.04	.05
CP Group Standard Deviation	6.68	9.17	.09	.11	.08	.09

C. Average Fundamental Frequencies

	Max phonations	2X Max phonations	Conversational sentences	0.5X Sentences	2X Sentences	4X Sentences
Control Group Mean	231.35	269.47	239.56	226.62	284.05	331.26
CP Group Mean	275.08	322.12	279.18	221.58	303.43	323.50
Control Group Standard Deviation	34.92	43.42	14.03	13.11	22.71	51.27
CP Group Standard Deviation	34.37	50.07	20.30	53.86	51.78	33.53

3.1: ANOVA results

An exploratory one-way within-subjects ANOVA was performed for each group to determine whether there were within-subjects differences for each dependent variable across loudness levels and tasks. The statistically significant within-subjects effects for the group with CP and the control group are listed in Table 3. The ANOVA determined that in the group with CP, mean F0 increased during a sentence repetition task as perceived vocal loudness changed. Pairwise comparisons are listed in Table 4 for both groups of participants. These comparisons suggest that there is a trend-level decrease in average F0 from conversational to perceived half-conversational loudness and that there is a significant increase in average F0 from conversational loudness to perceived twice conversational loudness and perceived four times conversational loudness. The repeated measures ANOVA also determined that in the control group, average F0 for maximum phonation duration increased, average F0 for sentences increased, and vowel duration for sentences increased as perceived vocal loudness changed. Pairwise comparisons (Table 4) revealed that specifically, there was a significant increase in average F0 from conversational loudness to perceived twice conversational loudness during a maximum phonation duration task. Average F0 for sentences increased from conversational to perceived twice conversational and four times conversational loudness levels. Average F0 for sentences in the control group increased significantly from perceived half conversational to twice conversational and four times conversational loudness and increased on a trend-level from twice conversational to four times conversational perceived loudness level. In the control group, vowel duration decreased significantly from conversational to perceived half-conversational loudness and increased significantly from perceived half-conversational loudness to perceived twice conversational and four-times conversational loudness levels.

An additional One-Way ANOVA was performed for formant measures in each group. Statistically significant within-subjects effects for the group with CP and the control group were listed in Table 3. This analysis suggested in the group with CP, F1 values increased as perceived loudness changed during sentence repetition at 25% of vowel duration (for the vowels /aɪ/ and /ɛ/) and 75% of vowel duration (for the vowel /aɪ/). In the group with CP, F2 values may have increased as perceived loudness changed during sentence repetition at 75% of the vowel /æ/. In the typically developing children, the ANOVA revealed that as loudness changed, F1 increased at the midpoint of /aɪ/ and at 75% of /aɪ/. In the typically developing children, F2 changed at the midpoint and 75% of /ɛ/. Notably, F2 changed at 25% of sustained maximum phonation duration with changes in perceived loudness in typically developing children. There were no apparent formant changes across loudness conditions in the children with CP during maximum phonation duration according to this analysis.

Additional pairwise formant value comparisons are listed in Table 4. These comparisons also suggest that in the children with CP, most significant changes in F1 and F2 occurred when comparing conversational or half-conversational perceived vocal loudness to perceived 4X conversational loudness in sentence repetition. A similar result for the sentence repetition task is apparent in the control children, as all significant results occur when comparing twice or 4X perceived conversational loudness to a lower perceived loudness level.

Table 3: One-way ANOVA analysis statistically significant within-subjects effects for the group with CP and the control group.

Group	**Variable**	**Statistic**
CP	Average F0 for sentences	*$F(3,9) = 7.16$, $p<0.01$
CP	F2 at 75% of /æ/	*$F(3,9) = 5.78$, $p<0.05$
CP	F1 at 25% of /aɪ/	*$F(3,9) = 7.13$, $p<0.01$
CP	F1 at 75% of /aɪ/	*$F(3,9) = 5.40$, $p<0.05$
Control	Average F0 for maximum phonation duration	*$F(1,3) = 12.94$, $p<0.05$
Control	Average F0 for sentences	*$F(3,9) = 18.28$, $p<0.01$
Control	Vowel duration for sentences	*$F(3,9) = 17.91$, $p<0.01$
Control	F1 at midpoint of /aɪ/	*$F(3,9) = 8.33$, $p<0.01$
Control	F1 at 75% of /aɪ/	*$F(3,9) = 11.16$, $p<0.01$
Control	F2 at midpoint of /ɛ/	*$F(3,9) = 4.18$, $p<0.05$
Control	F2 at 75% of /ɛ/	*$F(3,9) = 4.43$, $p<0.05$
Control	F2 at 25% of sustained maximum phonation duration	*$F(1,3) = 11.97$, $p<0.05$

Table 4: One-Way ANOVA Within-Subjects F0, vowel duration, and formant pairwise comparisons. Organized by task, variable of interest, and condition. A significant effect is accepted as $p \leq .05$.

Group	**Variable**	**Condition 1**	**Condition 2**	**Statistic**
CP	Average sentence F0	Half Conversational	2X Conversational	*$t(3) = -3.39$, $p<0.05$
CP	Average sentence F0	Half Conversational	4X Conversational	*$t(3) = -3.55$, $p<0.05$

Control	Average max phonation F0	Conversational	2X Conversational	**t*(3) = -3.597, *p*<0.05
Control	Average sentence F0	Half Conversational	2X Conversational	**t*(3) = -9.01, *p*<0.05
Control	Average sentence F0	Half Conversational	4X Conversational	**t*(3) = -5.37, *p*<0.05
Control	Average sentence F0	Conversational	2X Conversational	**t*(3) = -5.22, *p*<0.05
Control	Average sentence F0 for	Conversational	4X Conversational	**t*(3) = -3.76, *p*<0.05
Control	Average sentence vowel duration	Half Conversational	Conversational	**t*(3) = 7.73, *p*=0.005
Control	Average sentence vowel duration	Half Conversational	2X Conversational	**t*(3) = -5.54, *p*<0.05
Control	Average sentence vowel duration	Half Conversational	4X Conversational	**t*(3) = -5.21, *p*<0.05
CP	F2 at 75% of /æ/ duration	Half Conversational	Conversational	**t*(3) = 3.18, *p*=0.05
CP	F1 at 25% of /aɪ/ duration	Half Conversational	4X Conversational	**t*(3) = -5.28, **p*<0.05
CP	F1 at 25% of /aɪ/ duration	Conversational	4X Conversational	**t*(3) = -5.07, **p*<0.05
CP	F1 at 75% of /aɪ/ duration	Half Conversational	2X Conversational	**t*(3) = -4.92, **p*<0.05
CP	F1 at 75% of /aɪ/ duration	Half Conversational	4X Conversational	**t*(3) = -3.28, **p*<0.05
Control	F2 at 25% of maximum phonation duration	Conversational	2X Conversational	**t*(3) = -3.50, *p*<0.05
Control	F2 at midpoint of /ɛ/ duration	Half Conversational	Conversational	*t*(3) = -2.85, *p*=0.065
Control	F2 at 75% of /ɛ/ duration	Conversational	2X Conversational	*t*(3) = -2.46, *p*=0.091
Control	F2 at 75% of /ɛ/ duration	Conversational	4X Conversational	*t*(3) = -2.71, *p*=0.073
Control	F1 at midpoint of /aɪ/ duration	Conversational	4X Conversational	**t*(3) = -3.49, *p*<0.05
Control	F1 at 75% of /aɪ/ duration	Half Conversational	2X Conversational	**t*(3) = -5.29, *p*<0.05
Control	F1 at 75% of /aɪ/ duration	Half Conversational	4X Conversational	**t*(3) = -3.36, *p*<0.05

Control	F1 at 75% of /aɪ/ duration	Conversational	2X Conversational	*$t(3) = -6.20$, $p<0.01$
Control	F1 at 75% of /aɪ/ duration	Conversational	4X Conversational	*$t(3) = -3.26$, $p<0.05$

3.2: Intermuscular coherence individual results and visual trends

Intercostal-oblique raw intermuscular coherence values for each participant group in the medium frequency bandwidth (15-59Hz) were plotted to investigate visual trends in intercostal-oblique intermuscular coherence during sentence tasks (Figure 4) and maximum phonation duration tasks (Figure 5) at all perceived loudness levels. In the children with CP, intermuscular coherence during sentence repetition remained relatively stable across perceived loudness conditions, except for at 4X conversational loudness where it appeared to decrease. Typically developing children appeared to have stable intermuscular coherence values across sentence repetition conditions. During maximum phonation duration, the children with CP had visually higher intermuscular coherence than the typically developing children. Neither group’s intermuscular coherence values seemed to change with increased perceived maximum phonation duration loudness.

Figure 4: Effects of perceived vocal loudness on intercostal-oblique intermuscular coherence in children with CP and typically developing children during a sentence repetition task.

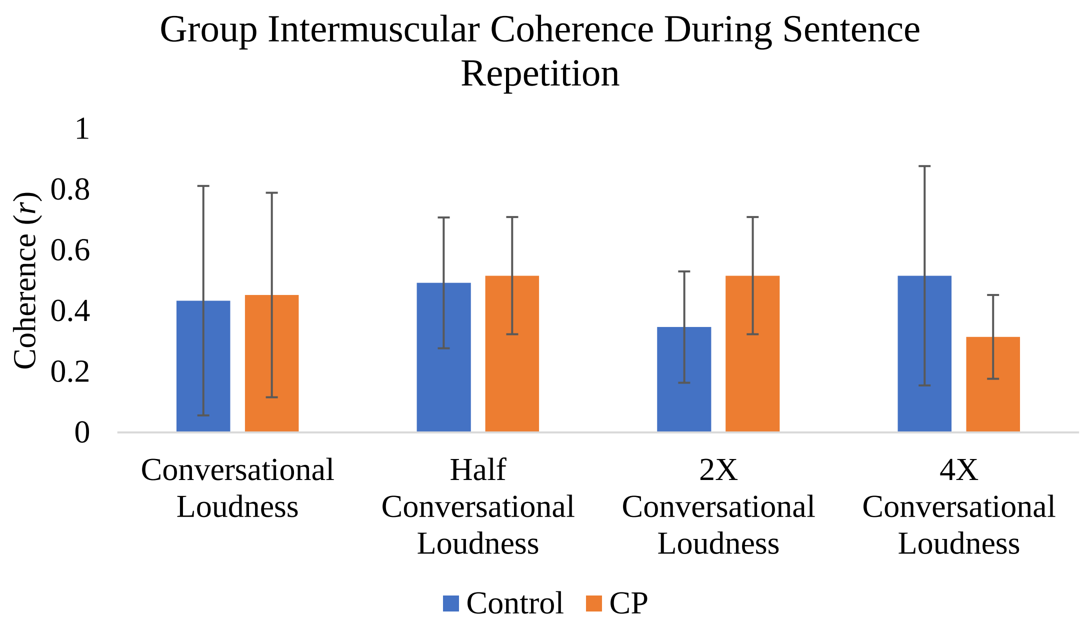
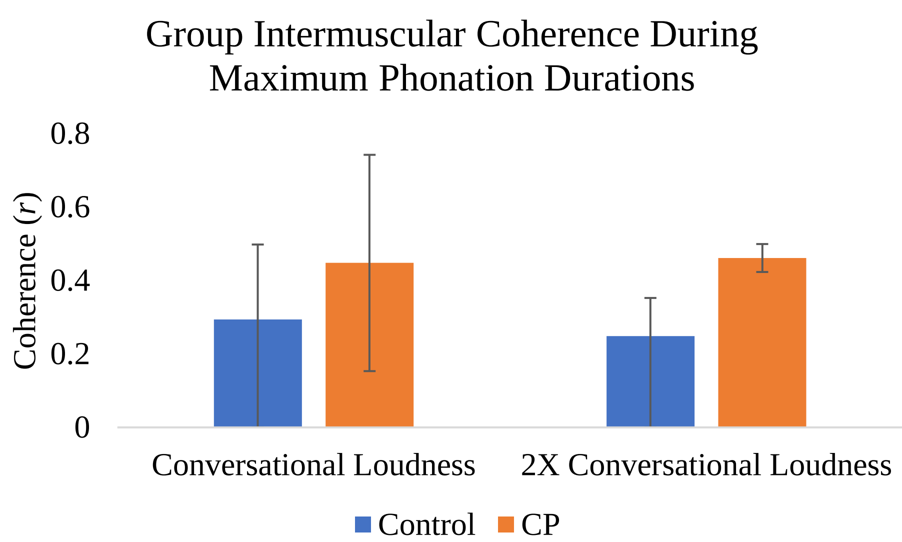


Figure 5: Effects of perceived vocal loudness on intercostal-oblique intermuscular coherence in children with CP and typically developing children during a sustained maximum phonation duration task.



Individual raw intermuscular-coherence values in the 15-59Hz range were also plotted for both groups in the sentence task (Figure 6) and the phonation task (Figure 7). It appears that there is considerable individual variability in coherence across loudness levels. Visually, the twelve-year-old control participants seem to have greater and more stable intermuscular coherence than the ten and eight-year-old control participants during sentence tasks. Additionally, during maximum phonation duration tasks the older control group children seem to have more coherence during conversational loudness compared to perceived twice conversational loudness, while the younger control group children show the reverse pattern. In the children with CP, it appears that age did not play as much of a role in the visual trends of intermuscular coherence as it did with the control group. The results seem to be more variable in this group. Participants F1201EL and F1001EL displayed a visual decrease in coherence from conversational to perceived twice conversational loudness during the sentence task, but an increase in coherence for the perceived four times conversational loudness condition. M0801EL showed an increase in coherence from conversational to perceived four times conversational loudness as well. F1001EL displayed a decrease in coherence from conversational to perceived twice and four times conversational loudness levels. In the maximum phonation task, F1201EL demonstrated an increase in coherence from conversational to perceived twice conversational loudness, while F1001EL displayed the opposite pattern. Overall, the children with CP demonstrated more variability in intermuscular coherence values across tasks. This variability may explain the visual lack of change in coherence across loudness levels observed in the group plots.

Figure 6: Raw coherence values for each participant during a sentence repetition task. No intermuscular coherence data points were available for participants M0801EL and M0801CL during the perceived half conversational and twice conversational loudness conditions.

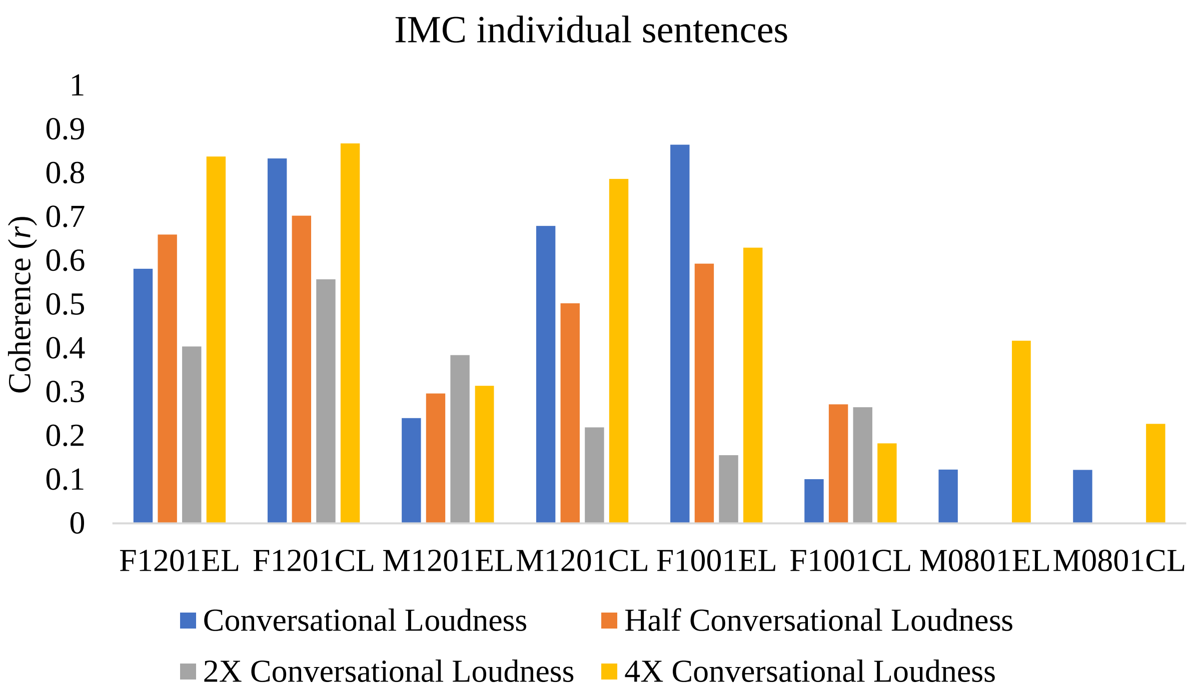
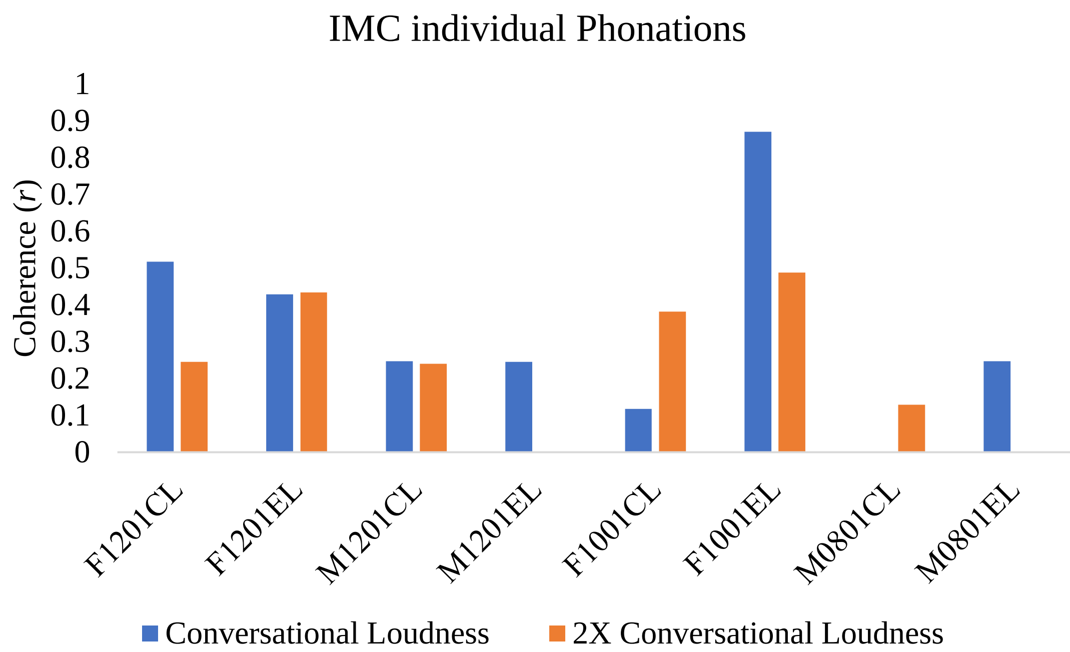


Figure 7: Raw intercostal-oblique intermuscular coherence values for each participant during the sustained maximum phonation duration task. No intermuscular coherence data points were available for participant M0801CL during the conversational loudness condition. No data points were available for participants M1201EL and M0801EL during the 2X conversational loudness condition.



3.3: Acoustic visual trends

Acoustic data were plotted to investigate visual trends across perceived loudness levels in each task. Figure 8 displays average vowel durations for each group of participants. It appears that the children with CP had longer vowel durations than the typically developing children during the sentence repetition task, and these vowel durations remained consistent across loudness conditions. Vowel durations appear to have remained stable across loudness conditions, except in perceived half conversational loudness where they are shorter. Figure 9 demonstrates phonation durations for both groups across perceived vocal loudness conditions. It is clear that individuals with CP as a group have shorter maximum phonation durations than their typically developing peers. However, there is also more variability in the CP group compared to the control group. It also appears that while children with CP increase duration as perceived phonation loudness increases, typically developing children's durations remain the same.

Figure 8: Effects of perceived vocal loudness on average vowel duration in children with CP and typically developing children during a sentence repetition task.

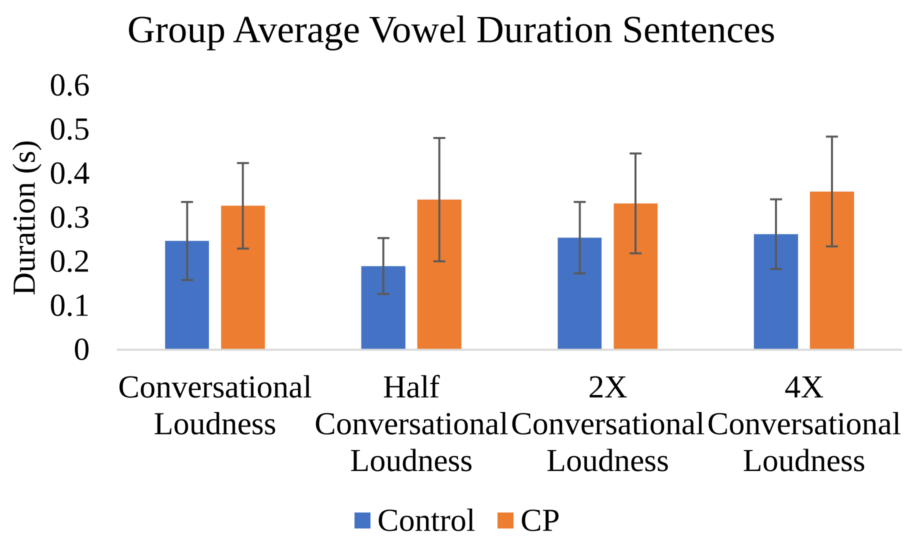


Figure 9: Effects of perceived vocal loudness on average maximum phonation duration in children with CP and typically developing children.

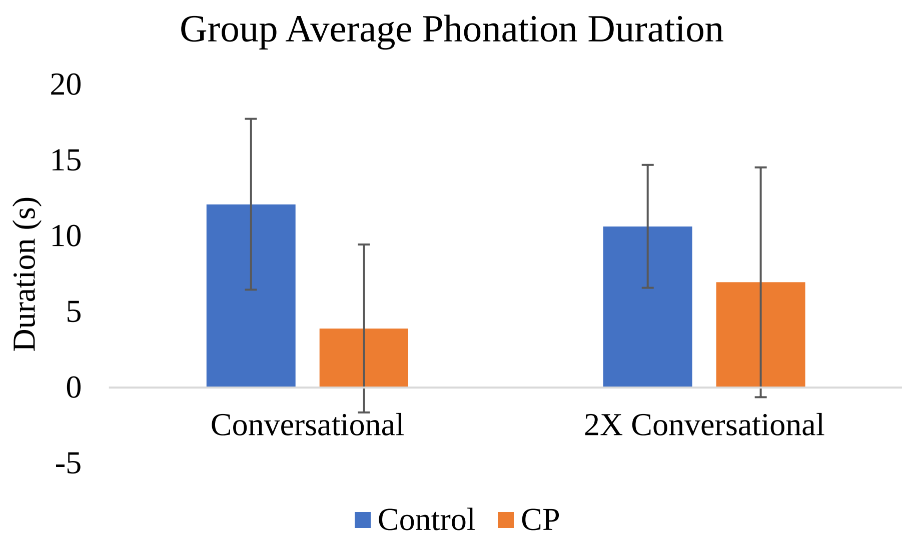


Figure 10 and Figure 11 display average group F0 across sentence and phonation tasks, respectively. It appears that the CP group and the control group had similar F0 results with respect to the sentence and maximum phonation duration tasks. In both groups, it seems that F0 increased with increasing loudness. The CP group may have more F0 variability during the sentence task.

Figure 10: Effects of perceived vocal loudness on average F0 in children with CP and typically developing children during a sentence repetition task.

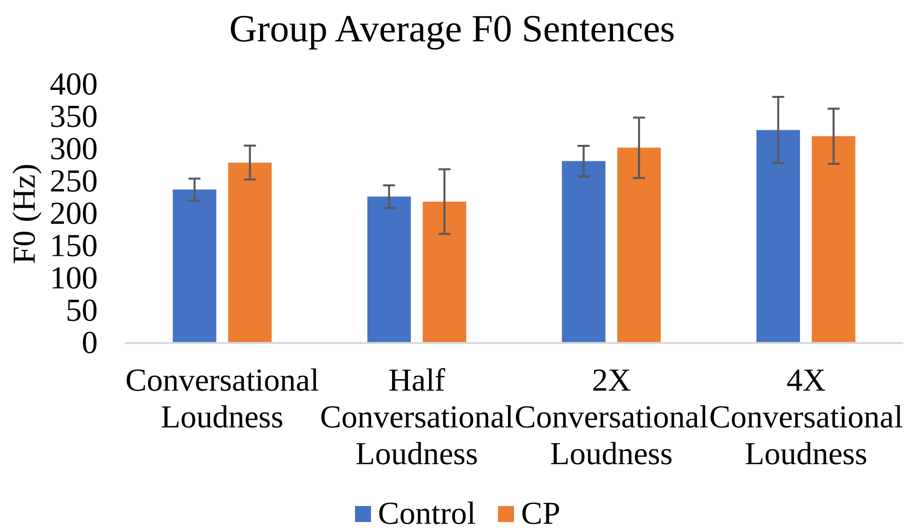
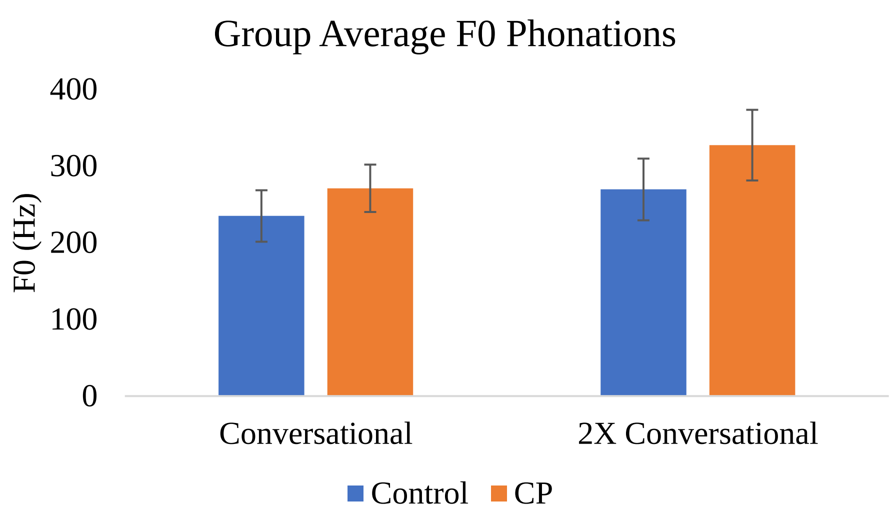


Figure 11: Effects of perceived vocal loudness on average F0 in children with CP and typically developing children during a sustained maximum phonation duration task.



Lastly, Figure 12 and Figure 13 graph the vowel midpoint F1 and F2 vowels for the group with CP and the control group, respectively for sentence task vowels (/aɪ/, /ɛ/, and /æ/) and the phonation task vowel, /ɑ/. These values are graphed for conversational and twice perceived conversational loudness levels, since these were the only conditions used for sustained maximum phonation duration. In both groups, the vowels become more peripheral with increased perceived vocal loudness. Based off these plots, it appears that the children with CP may have increased the F1 value of /ɑ/ with increased perceived vocal loudness dramatically compared to the typically developing children. They also seemed to increase the F2 value of this vowel less than their typically developing peers with increased loudness.

Figure 12: Effects of perceived vocal loudness on F1 and F2 values at the midpoint of the duration of vowels /aɪ/, /ɛ/, /æ/ for the sentence repetition task, and the vowel /ɑ/ for the maximum phonation duration task, in children with CP.

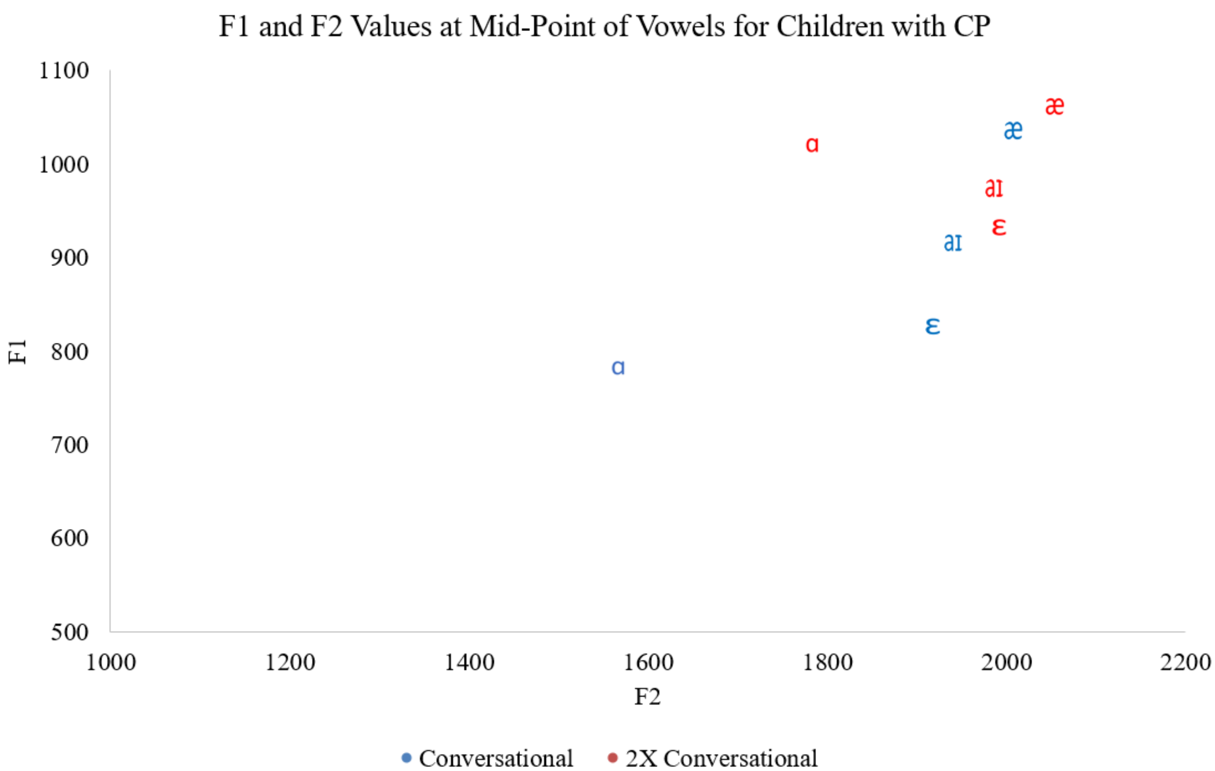
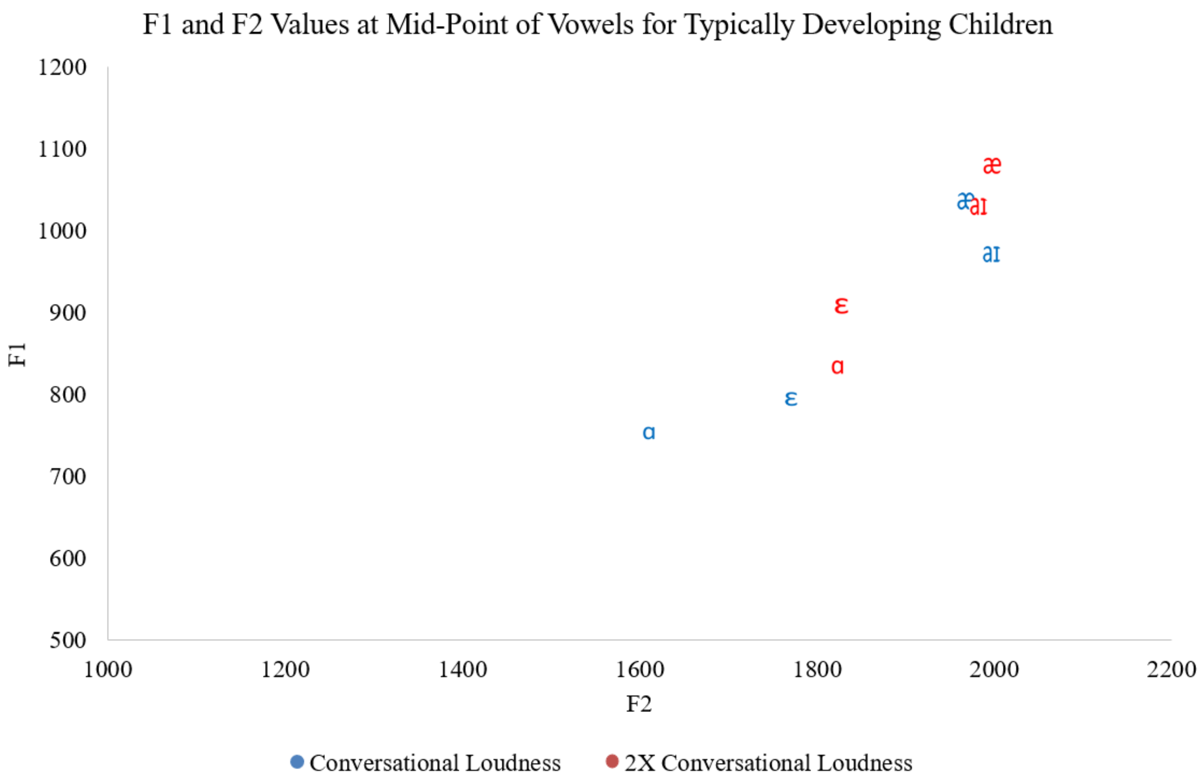


Figure 13: Effects of perceived vocal loudness on F1 and F2 values at the midpoint of the duration of vowels /aɪ/, /ε/, /æ/ for the sentence repetition task, and the vowel /ɑ/ for the maximum phonation duration task, in typically developing children.



3.4: Acoustics individual results (paired *t*-tests)

Paired samples *t*-tests were collected to compare performance across tasks for each individual participant for vowel duration and average F0. The goal of this analysis was to determine whether F0 and vowel durations changed with increasing perceived vocal loudness for each participant. The significant differences are outlined in Table 5 for the participants with CP and Table 6 for the age- and gender-matched control participants. Based on this analysis it appears that all participants with and without cerebral palsy had a significant or trend-level difference in their sentence task vowel durations from conversational to perceived twice conversational loudness. Additionally, each individual participant with CP showed a significant or trend-level difference in sentence task average F0 from conversational to perceived half conversational and four times conversational loudness, from perceived half conversational to twice and four times conversational loudness, and from perceived twice to perceived four times conversational loudness. Each participant in the control group showed a significant difference in the sentence task vowel duration from conversational to perceived half conversational loudness and from perceived half conversational to twice conversational loudness. The control participants each also had significant differences in sentence task average F0 from conversational to perceived twice and four times conversational loudness levels and from perceived half conversational to twice and four times conversational loudness.

Table 5: Experimental Group Paired *t*-Test Results. Paired samples *t*-test acoustic results for each participant with cerebral palsy (F1001EL, F1201EL, M0801EL, and M1201EL). Significant results with a 2-tailed *p*-value of less than 0.05 and trends with a 2-tailed *p*-value of less than 0.10 were included.

Participant	**Task**	**Variable**	**Condition 1**	**Condition 2**	***t*-value**	**df**	**2-tailed statistic**
F1001EL	Sentence	Vowel duration	Conversational	2X Conversational	-3.71	14	*$p<0.01$
F1001EL	Sentence	Vowel duration	Conversational	4X Conversational	-5.24	14	*$p<0.01$
F1001EL	Sentence	Vowel duration	Half Conversational	2X Conversational	-1.88	14	$p=0.081$
F1001EL	Sentence	Vowel duration	Half Conversational	4X Conversational	-3.31	14	*$p<0.01$
F1001EL	Sentence	Average F0	Conversational	Half Conversational	11.11	14	*$p<0.01$
F1001EL	Sentence	Average F0	Conversational	2X Conversational	-9.52	14	*$p<0.01$
F1001EL	Sentence	Average F0	Conversational	4X Conversational	-20.70	14	*$p<0.01$
F1001EL	Sentence	Average F0	Half Conversational	2X Conversational	-21.24	14	*$p<0.01$
F1001EL	Sentence	Average F0	Half Conversational	4X Conversational	-25.778	14	*$p<0.01$

F1001EL	Sentence	Average F0	2X Conversational	4X Conversational	-13.616	14	*p<0.01
F1201EL	Max Phonation	Vowel duration	Conversational	2X Conversational	3.66	2	p=0.067
F1201EL	Sentence	Vowel duration	2X Conversational	4X Conversational	101.19	14	*p<0.01
F1201EL	Sentence	Average F0	Conversational	Half Conversational	31.24	14	*p<0.01
F1201EL	Sentence	Average F0	Conversational	4X Conversational	-4.41	14	*p<0.01
F1201EL	Sentence	Average F0	Half Conversational	2X Conversational	-51.44	14	*p<0.01
F1201EL	Sentence	Average F0	Half Conversational	4X Conversational	-20.89	14	*p<0.01
F1201EL	Sentence	Average F0	2X Conversational	4X Conversational	-4.02	14	*p<0.01
M0801EL	Max Phonation	Average F0	Conversational	2X Conversational	-5.05	3	*p<0.05
M0801EL	Sentence	Vowel Duration	Conversational	2X Conversational	2.46	14	*p<0.05
M0801EL	Sentence	Vowel Duration	Conversational	4X Conversational	1.82	14	p=0.9
M0801EL	Sentence	Vowel Duration	Half Conversational	2X Conversational	3.56	12	*p<0.01
M0801EL	Sentence	Average F0	Conversational	Half Conversational	3.28	12	*p<0.01
M0801EL	Sentence	Average F0	Conversational	2X Conversational	-9.69	13	*p<0.01
M0801EL	Sentence	Average F0	Conversational	4X Conversational	-2.74	14	*p<0.05
M0801EL	Sentence	Average F0	Half Conversational	2X Conversational	-9.14	11	*p<0.01
M0801EL	Sentence	Average F0	Half Conversational	4X Conversational	-3.29	12	*p<0.01
M0801EL	Sentence	Average F0	2X Conversational	4X Conversational	2.58	13	*p<0.05
M1201EL	Sentence	Vowel duration	Conversational	2X Conversational	-1.86	11	p=0.9
M1201EL	Sentence	Average F0	Conversational	Half Conversational	5.62	11	*p<0.01
M1201EL	Sentence	Average F0	Conversational	2X Conversational	1.97	11	p=0.075
M1201EL	Sentence	Average F0	Half Conversational	2X Conversational	-3.23	14	*p<0.01

M1201EL	Sentence	Average F0	Half Conversational	4X Conversational	-4.71	14	*$p<0.01$
M1201EL	Sentence	Average F0	2X Conversational	4X Conversational	-2.22	14	*$p<0.05$

Table 6: Control Group Paired *t*-Test Results. Paired samples *t*-test acoustic results for each age- and gender-matched control participant without cerebral palsy (F1001CL, F1201CL, M0801CL, and M1201CL). Significant results with a 2-tailed *p*-value of less than 0.05 and trends with a 2-tailed *p*-value of less than 0.10 were included.

Participant	**Task**	**Variable**	**Condition 1**	**Condition 2**	***t*-value**	**df**	**2-tailed statistic**
F1001CL	Max phonation	Average F0	Conversational	2X Conversational	3.80	2	$p=0.063$
F1001CL	Sentence	Vowel duration	Conversational	Half Conversational	7.85	14	*$p<0.01$
F1001CL	Sentence	Vowel duration	Conversational	2X Conversational	2.85	14	*$p<0.05$
F1001CL	Sentence	Vowel duration	Half conversational	2X Conversational	-5.75	14	*$p<0.01$
F1001CL	Sentence	Vowel duration	Half conversational	4X Conversational	-1.89	14	$p=0.08$
F1001CL	Sentence	Average F0	Conversational	Half conversational	7.71	14	*$p<0.01$
F1001CL	Sentence	Average F0	Conversational	2X Conversational	-10.14	14	*$p<0.01$
F1001CL	Sentence	Average F0	Conversational	4X Conversational	-3.56	14	*$p<0.01$
F1001CL	Sentence	Average F0	Half Conversational	2X Conversational	-14.43	14	*$p<0.01$
F1001CL	Sentence	Average F0	Half Conversational	4X Conversational	-8.75	14	*$p<0.01$
F1201CL	Max Phonation	Vowel duration	Conversational	2X Conversational	3.55	2	$p=0.071$
F1201CL	Max phonation	Average F0	Conversational	2X Conversational	-36.74	2	*$p<0.01$
F1201CL	Sentence	Vowel duration	Conversational	Half Conversational	3.88	14	*$p<0.01$
F1201CL	Sentence	Vowel duration	Half Conversational	2X Conversational	-6.38	14	*$p<0.01$
F1201CL	Sentence	Vowel duration	Half Conversational	4X Conversational	-6.84	14	*$p<0.01$

F1201CL	Sentence	Average F0	Conversational	2X Conversational	-12.76	14	*p<0.01
F1201CL	Sentence	Average F0	Conversational	4X Conversational	-16.250	14	*p<0.01
F1201CL	Sentence	Average F0	Half Conversational	2X Conversational	-17.90	14	*p<0.01
F1201CL	Sentence	Average F0	Half Conversational	4X Conversational	-16.97	14	*p<0.01
F1201CL	Sentence	Average F0	2X Conversational	4X Conversational	-11.04	14	*p<0.01
M0801CL	Max Phonation	Average F_0	Conversational	2X Conversational	-3.88	2	p=0.06
M0801CL	Sentence	Vowel duration	Conversational	Half Conversational	6.80	8	*p<0.01
M0801CL	Sentence	Vowel duration	Conversational	2X Conversational	-2.75	8	*p<0.05
M0801CL	Sentence	Vowel duration	Conversational	4X Conversational	-2.87	8	*p<0.05
M0801CL	Sentence	Vowel duration	Half Conversational	2X Conversational	-9.60	8	*p<0.01
M0801CL	Sentence	Vowel duration	Half Conversational	4X Conversational	-5.94	8	*p<0.01
M0801CL	Sentence	Average F0	Conversational	Half Conversational	12.04	8	*p<0.01
M0801CL	Sentence	Average F0	Conversational	2X Conversational	-10.71	8	*p<0.01
M0801CL	Sentence	Average F0	Conversational	4X Conversational	-19.70	8	*p<0.01
M0801CL	Sentence	Average F0	Half Conversational	2X Conversational	-22.27	8	*p<0.01
M0801CL	Sentence	Average F0	Half Conversational	4X Conversational	-34.91	8	*p<0.01
M0801CL	Sentence	Average F0	2X Conversational	4X Conversational	-7.68	8	*p<0.01
M1201CL	Sentence	Vowel duration	Conversational	Half Conversational	3.67	14	*p<0.01
M1201CL	Sentence	Vowel duration	Conversational	2X Conversational	-4.83	14	*p<0.01
M1201CL	Sentence	Vowel duration	Conversational	4X Conversational	-3.27	14	*p<0.01
M1201CL	Sentence	Vowel duration	Half Conversational	2X Conversational	-5.27	14	*p<0.01
M1201CL	Sentence	Vowel duration	Half Conversational	4X Conversational	-5.53	14	*p<0.01

M1201CL	Sentence	Average F0	Conversational	Half Conversational	2.96	14	*p=0.01
M1201CL	Sentence	Average F0	Conversational	2X Conversational	-8.54	14	*p<0.01
M1201CL	Sentence	Average F0	Conversational	4X Conversational	-18.70	14	*p<0.01
M1201CL	Sentence	Average F0	Half Conversational	2X Conversational	-12.98	14	*p<0.01
M1201CL	Sentence	Average F0	Half Conversational	4X Conversational	-20.59	14	*p<0.01
M1201CL	Sentence	Average F0	2X Conversational	4X Conversational	-13.30	14	*p<0.01

CHAPTER IV: DISCUSSION

4.0: Hypotheses revisited

The first hypothesis was that intercostal-oblique coherence, F0 average, and vowel durations would increase and vowel space would become more peripheral with increased perceived vocal loudness levels for all participant groups across tasks. This hypothesis was partially supported. The second hypothesis was that children with CP would make loudness adjustments by increasing neuromuscular drive to the chest wall as measured by changes in intermuscular coherence, while typically developing children would make laryngeal adjustments requiring more sophisticated cortico-muscular coordination, as evidenced by greater acoustic changes across loudness conditions. This hypothesis was partially supported as well.

4.1: Intercostal-oblique intermuscular coherence

According to the exploratory repeated measures one-way analysis, intercostal-oblique intermuscular coherence in the medium frequency bandwidth (15-59Hz) remained stable at all perceived loudness levels for both groups of participants. This is likely because of the limited sample size in the present study. However, a visual trend analysis revealed that there was considerable individual variability in intermuscular coherence across participants. Despite the variability, tentative conclusions can be made. It seemed that the older participants, especially the twelve-year-olds, had more stable patterns of coherence across loudness levels compared to the younger participants in both the control group and the group with CP. This is a similar result to Tam (2017) who did not find any differences in peak coherence in the 15-59Hz bandwidth in healthy adult speakers during sentence repetition tasks across loudness conditions but did find differences in coherence in healthy six to ten-year-old participants across loudness levels. Tam

(2017) concluded that healthy adults may have more highly developed corticospinal control of the speech mechanism that is stable even with changes in cued vocal loudness when compared to healthy children. It is possible that the twelve-year-old participants in the present study were approaching this more advanced neuromuscular control for speech that is observable in adults. The eight and ten-year-old participants, who have considerably different speech mechanisms than do adults (Stathopolous & Sapienza, 1997) seemed to have more variable intercostal-oblique intermuscular coherence for various cued loudness tasks.

4.2: Acoustics

It appears that the children with CP adjusted their perceived vocal loudness levels by adjusting pitch levels but not by increasing vowel durations during sentences. Individuals in the control group seemed to adjust their vocal loudness levels by increasing F0 in maximum phonation and sentence duration, as well as by increasing vowel duration in sentences. The repeated measures one-way ANOVA analysis suggested that average F0 changed significantly across perceived loudness conditions in both participant groups during the sentence task (Table 4) and increased in the control group during the maximum phonation task as well. This is unsurprising as Archibald (2011) showed that all of these participants did in fact change their sound pressure levels for the twice and four times conversational levels during sentences and for the twice conversational loudness level during maximum phonation duration. It is well known that fundamental frequency is dependent on sound pressure level and increases with increased subglottal pressure (Dromey & Ramig, 1998; Titze, 1989). Interestingly, in the group with CP, average F0 did not increase during maximum phonation duration, and during sentences the conversational average F0 was no different from the twice or four times conversational loudness levels, despite increases in sound pressure level. This result could point to greater laryngeal control of loud speech in healthy children compared to children with motor speech disorders and supports part of the second hypothesis made in the present study.

Vowel duration increased significantly in only one condition (from perceived half conversational loudness to conversational loudness sentences) in the control group, and not at all in the group with CP. This could be because children are already phonating at their maximum performance capacity during conversational speech, and their duration may not increase more within increased loudness. This result is similar to findings from Dromey and Ramig (1998) who found that utterance duration increased from soft to conversational loudness levels in healthy adults, but when speech became even louder there were no significant increases in utterance duration. This result is also supported by results from Levy et al. (2017) who found that cues to use a “strong voice” led to increases in sound pressure level but minimal changes in word duration during word repetition in children with dysarthria secondary to CP.

The repeated measures ANOVA also suggests that there are differences in formant adjustments with increased perceived vocal loudness in children with CP and typically developing children during sustained maximum phonation tasks. According to this analysis, typically developing children may increase F2 values with increased perceived vocal loudness for sustained productions of the vowel /ɑ/. Thus, it appears that typically developing children may adjust the shapes of their vocal tracts while speaking at greater than perceived conversational loudness. However, children with CP may not make the same adjustment during this task. This finding supports the overarching hypothesis that typically developing children make more refined acoustic adjustments than their peers with CP while adjusting vocal loudness levels. However, as supported by the ANOVA analysis and the scatterplots in Figure 12 and

Figure 13, children with CP may have similar formant changes during sentence repetition tasks compared to typically developing children.

Furthermore, the paired *t*-test analysis revealed that children with CP had fewer significant pairwise effects compared to their age- and gender-matched peers in general with respect to average F0 and vowel durations. There were considerable individual differences in which contrasts were significant, but all participants displayed significant differences or trends in vowel duration from conversational to perceived twice conversational loudness on an individual level. These individual differences could account for some of the lack of significance found in the ANOVA analysis.

CHAPTER V: CONCLUSION

The results from this study may offer baseline-level support for more intensive vocal loudness training programs. Additionally, increasing vocal loudness over a single session may not be sufficient enough to invoke increases in intermuscular coherence in children with and without CP. Mager (2015) found that there was an increase in intercostal-oblique intermuscular coherence during an untrained speech task (repeating the sound *pataka*) in children with CP following LSVT LOUD treatment. The children completed weeks of intervention and maintenance before changes in intermuscular coherence were observed. This could be because of corticospinal plasticity that is mediated by experiences of skilled motor strength training (Adkins et al., 2006), as well as increases in speech-related cortical white-matter integrity following intensive vocal loudness training in children with cerebral palsy (Reed et al., 2017). In addition, the findings suggest that older children and typically developing children seem to make more laryngeal adjustments when producing loud speech compared to children with CP, who may make minimal laryngeal adjustments and more corticospinal control adjustments during cued loudness tasks.

In conclusion, it seems that children with and without CP may make neuromuscular adjustments to increase vocal loudness in a single session of sentence repetition and maximum phonation duration tasks, as is tentatively supported by visual trends in intercostal-oblique intermuscular coherence in the medium frequency bandwidth. Typically developing children seem to make laryngeal adjustments to increase vocal loudness. Children with CP appear to do this as well, but to a lesser degree. These results point to a need to look at more long-term and intensive loudness interventions in children with motor speech disorders secondary to CP. They also serve as a baseline of laryngeal and physiological measures for these kinds of treatments.

Future studies may include more participants to strengthen the power of the statistical analyses of the data. Additionally, it would be informative to collect these data before and after an intensive loudness-based therapy like LSVT LOUD. This could provide insights into how biomechanical and physiological loudness adaptations are made pre- and post-treatment and whether they are conducive to vocal health in children with motor speech disorders secondary to CP.

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