IMPACT OF BREATH GROUP CONTROL ON THE SPEECH OF NORMALS AND INDIVIDUALS WITH CEREBRAL PALSY

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Abstract

Dysarthria is one of the most common signs of speech impairment in the cerebral palsy (CP) population. Facilitating strategies for speech enhancement in this population often include training on speech breathing. Treatment efficacy studies with cross-system measures in this population are needed for improved understanding and management of the interrelationship between respiratory, phonatory, and articulatory systems. The purpose of this study was to investigate the effect of breath group control on the coordination of articulatory and phonatory muscles and the acoustic measures related to speech and voice quality. A simultaneous acoustic, electroglottographic (EGG), and marker-based facial tracking recording system was employed to monitor the speech production behaviors of four adults with CP and 16 neurologically healthy controls. Subjects were instructed to perform three tasks, each containing speech targets with a voiceless plosive (/p/, /t/, or /k/) preceding a vowel (/i/, /a/, /u/, or /ɔ/). Task 1 consisted of a short reading passage embedded with target vowels without cueing from breath group markers. Task 2 included reading a series of monosyllabic and 3-syllable or 5-syllable non-speech words with the speech targets. Task 3 included reading the same short passage from Task 1 with cueing from breath group markers separating the passage into phrases with no more than five syllables per phrase. Measures from the acoustic, EGG and facial tracking recordings of the first and last syllable of all syllable trains produced in the non-speech task and the target vowels in the passage reading task were examined. Acoustic measures included voice onset time (VOT), vowel duration, fundamental frequency (F0), percent jitter (%jitter), percent shimmer (%shimmer), signal-to-noise ratio (SNR), and frequencies of Formants one and two (F1 and F2). EGG measures included speed quotient (SQ) and open quotient (OQ). Facial tracking measures consisted of maximum jaw displacement. Individual and averaged data were submitted to a series of two-way Analysis of Variances (ANOVAs) or two-way Repeated Measures ANOVAs to determine the effects of the relative position of an utterance in the breath group and the place of articulation of the consonants involved. In addition, mean vowel spaces derived from all three tasks were examined. Results revealed significant changes of VOT, F1, F2, SNR and SQ as a function of position. Significant changes of VOT, vowel duration, F2, F0, %jitter, %shimmer, and maximum jaw displacement as a function of place of articulation were also evident. In particular, breath group control was found to result in expansion of vowel space, especially for individuals with CP. These findings suggest that proper phrasing enhances articulatory and phonatory stability, providing empirical evidences in support of its usage in treating individuals with CP.

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Chapter 1. Introduction

This study concerns how breath group control may affect the speech and voice of individuals with cerebral palsy (CP) as compared with speakers with no speech impairment. This chapter provides an overview of the rationale behind the investigation, a literature review, and an outline of the research question and its importance and related aims and hypotheses.

1.1 Overview

Cerebral Palsy is a collective term encompassing a group of neurological syndromes resulting from abnormalities in the brain development or an acquired non-progressive cerebral lesion (Bax, 1964; Bobath, 1980; Platt & Pharoah, 1995). It is characterised by anomalous control of movement or posture (Palisano et al., 1997). The condition typically originates during the antenatal, perinatal, or postnatal periods (Denhoff, 1976). In most cases, the aetiology of CP remains unknown because CP is a range of specific symptoms rather than a disease (Hardy, 1983). Cerebral palsy is commonly associated with dysarthria, a deficit in speech motor control. Dysarthria is characterized by disturbances in speech muscular control due to paresis, paralysis, slowness, in-coordination, or aberrant tone of muscles (Duffy, 1995). Dysarthric speech may indicate impairment of one or more motor processes of speech production, including respiration, phonation, resonance, articulation, and prosody (Duffy, 1995). The execution of individual speech musculatures may be slow, weak, and uncoordinated (Duffy 1995). Among all the modalities involved in speech production, the respiratory system was most often found to be compromised in the CP population (Wolfe, 1950). As a result, speech treatments often include exercises aiming to improve the strength and co-ordination of the respiratory muscles as well as various strategies facilitating better breath control to enhance speech production (Workinger, 2005). However, although the relationship between speech breathing and speech naturalness or intelligibility has been examined in speakers with dysarthria in general (e.g., Bellaire, Yorkston & Beukleman, 1986; Yunusova, Weismer, Kent & Rusche, 2005) and individuals with CP (e.g. Pennington, Smallman & Farrier, 2006), there are to date relatively few objective or instrumental studies on the speech and voice of individuals with CP in response to changes in breath group control. To provide the empirical data needed in support of an evidence-based practice and to induce further understanding of the relationship between speech breathing and speech and voice quality, this study employs a simultaneous cross-system recording technique to monitor speech and vocal behaviours to examine how breath group control may facilitate speech and voice enhancement in individuals with CP as well as neurologically healthy controls.

1.2. Literature Review

This literature review provides a theoretical framework for understanding why investigation of the effect of breath group control on oral-laryngeal coordination will enhance the speech management of individuals with CP in particular. This review covers topics related to cerebral palsy, breath control, speech measurement, and vowel working space.

1.2.1 Cerebral Palsy

The term "cerebral palsy" refers to a variety of symptoms resulting from abnormalities or lesions of the early developing brain (Bax, 1964; Bobath, 1980; Platt & Pharoah, 1995). Cerebral palsy is the most common physical disability in childhood, affecting approximately two per 1,000 live births (Cerebral Palsy Society of New Zealand, 2007). Despite major changes in neonatal and obstetric care causing a prominent decrease in prenatal mortality in recent years, the prevalence of CP remained unchanged (Blair, 2001; Hagberg, Hagberg, Beckung & Uvebrant, 2001). Approximately 7,000 individuals are currently diagnosed with CP in New Zealand, with two thirds of the affected population being over 21 years of age (Cerebral Palsy Society of New Zealand, 2007).

The aetiology of CP has been studied extensively. During the 1980s and 1990s, birth asphyxia was considered the primary cause of CP (Stanley, Blair & Alberman, 2000). Evidence suggests, however, that prenatal factors associated with birth asphyxia found in 70 to 80% of the cases of CP might be early manifestations of CP from different causes (Blair & Stanley, 1988; Stanley et al., 2000; Nelson, 1988). Risk factors frequently found to be associated with CP include low gestational age (Denhoff, 1976; Blair & Stanley, 1997; Hagberg et al., 2001), low Apgar scores (Nelson & Ellenberg, 1981), multiple gestation (Nelson & Grether, 1999), male gender (Blair & Stanley, 1997), iodine deficiency (Pharoah, Buttfield & Hetzel, 1971), perinatal exposure to methyl mercury (Amin-Zaki, Majeed, Elhassani et al., 1979; Stanley, 1997), maternal thyroid abnormalities (Blair & Stanley, 1993; Stanley, 1997), and intrauterine viral infection, such as rubella and cytomegalovirus (Denhoff, 1976; Hagberg & Mallard, 2000; Stanley, 1997). Amongst all risk factors for CP, low gestation age has been considered the most important one, with around 28 % of children with CP born before 32 weeks, as compared to 1 % of all births. However, the aetiology and pathology of this population remain largely unclear.

1.2.1.1 Types of Cerebral Palsy

A topographic distribution of the motor disorders, such as the differentiation among hemiplegia, diplegia, and tetraplegia, is often used to locate the various sites of the neuromotor disorders (Colver & Sethumadhavan, 2003). Based on the characteristics and manifestations of neuromotor disorders of the limbs, CP can also be classified based on the characteristics of muscle moments and tone of the individual. There are three major types of CP, namely, spastic, athetoid, and ataxic. Athetoid CP, also known as dyskinetic CP, is related to damage to the basal ganglia and characterized by involuntary extraneous movements. Ataxic CP is related to damage to the cerebellum and characterized by in-coordination of gross and fine motor movements. Athetoid CP and ataxic CP affect approximately 10 to 20% and 5 to 10% of the cases respectively (Cerebral Palsy Society of New Zealand, 2007). Spastic CP is related to damage to the motor area of the cortex and/or to the subcortical white matter (Rutherford, 1950) and characterised by stiff or rigid muscles and exaggerated, deep tendon reflexes (Levitt, 1995; Rutherford, 1950). Spastic CP is the most common type of CP, affecting approximately 70 to 80% of all cases (Cerebral Palsy Society of New Zealand, 2007; Colver & Sethumadhavan, 2003). Spastic diplegia is the main form of CP related to low gestational age.

1.2.1.2 Speech Characteristics

Dysarthria is the most common speech disorder associated with CP (Hardy, 1983). An estimate of 30% to 90% of individuals with CP was considered to exhibit reduced speech intelligibility and some form of dysarthric speech (Yorkston, Beukelman, & Bell, 1988; Kennes et al., 2002; Hustad et al., 2003). Individuals with CP often present with spastic or weak muscle tone, resulting in in-coordinated speech patterns, as shown in the presence of imprecise consonants, short phrases, and reduced rate of speech (Hardy, 1983; Love, 1992; Rutherford, 1950; Workinger, 2005). In adults, both articulatory coordination (Kent, Netsell, & Abbs, 1978) and prosody (Hardy, 1983) are commonly adversely affected. It appears that both articulatory control and oral-laryngeal co-ordination in individuals with CP are susceptible to disturbances in the speech muscular control including control of respiratory musculatures (Bobath, 1980; Love, 1992; Hardy, 1983; Solomon & Charron, 1998; Workinger, 2005).

1.2.2 Breath Control

Breath control, also referred to as breath or respiratory support, is related to an individual's respiratory function during speech production (Hardy, 1983; Spencer, Yorkston, & Duffy, 2003). The respiratory system has been described as "an elastic mechanical mechanism" (Hardy, 1983), which involves the precise co-ordination of various intrinsic and extrinsic respiratory muscles. These muscles are responsible for modifying the size of the thoracic cavity (Martini, 2004) and influence the amount of air pressure the required in speech production (Hardy, 1983; Solomon & Charron, 1998). This section will describe the relationship between breath control and speech production, breath control in individuals with CP, and current speech therapeutic approaches related to breath control.

1.2.2.1 Breath Control in Speech Production

Speech breathing refers to the respiratory mechanism involved during speech production, from increase of the air pressure in the lungs through inhalation before speech production to the change of air pressure throughout the speech production process (Hardy, 1983; Soloman & Charron, 1998). Speech is typically carried through exhaling air. Since periodic vocal fold vibration is essential in voice production, the ability to generate and sustain a sufficient air supply to build up subglottal pressure is critical to voice production. As normal voicing requires precise co-ordination of the laryngeal and respiratory system, the relationship between respiration and phonation has received a considerable amount of attention.

Impaired respiratory physiology have been shown to impact on various features of speech, including speech naturalness, fundamental frequency and speech loudness (Bellaire et al., 1986; Hardy, 1983; Hird & Hennessy, 2006; Milstein, Watson, 2004;

Spencer, et al., 2003; Watson, Ciccia, & Weismer, 2003). For example, Bellaire et al. (1986) examined the effect of breath group patterning on speech naturalness in the connected speech of a 20 year old male with mild dysarthria secondary to a close head injury. Prior to treatment, perceptual judgements indicated that the subject's speech was intelligible but often unnatural. A pre-treatment motor speech evaluation at nine months post injury revealed a deficit in the breathing and pausing patterns. Characteristics of the subject's speech included: (i) short breath group length, with the mean length of breath group from counting and reading of connected text being 4 and 5.1 words respectively, and (ii) large number of pauses with inhalation (93% as opposed to 63% in controls). In addition, the subject demonstrated the ability to increase the number of words to 23 in one breath during a counting task. After training on reading connected text provided with written cues on breathing and pausing with and without inhalation, the subject's speech was judged to be more natural and less monotonous by three speech-language therapists and the average breath group length increased to 9. 8 words per breath group, the number of pauses with inhalation decreased from 27 to 14, and the number of pauses without inhalation increased from two to 11. Bellaire et al. (1986) suggested that the perceived improvement in speech naturalness may be associated with an increase in the range of fundamental frequency and the length of the breath group.

The relationship between lung volume and speech and voice production has also been studied (Milstein, Watson, 2004, Watson, Ciccia, & Weismer, 2003). Lung volume, defined as the amount of air in the lungs, is affected by the passive recoil forces of the lungs and the active forces of the expiratory and inspiratory muscles. Lung volume is typically expressed in percentage of the vital capacity, with the lung volume increasing from 0% following maximal exhalation to 100% of the vital capacity following maximal inhalation. During conversational speech, subglottal pressure in adults is typically between 5 to 10 cm/H_2O (Weismer, 2007) and the lung volume for speech breathing when sitting upright have been reported to be approximately 60% of the vital capacity around the beginning and 35 to 40% towards the end of a breath group (Dromey & Ramig, 1998; Hixon, Goldman & Mead, 1973; Milstein & Watson, 2004; Watson, et al., 2003; Weismer, 2007).

Watson et al. (2003) examined the effect of lung volume on vowel duration, fundamental frequency (F0), frequencies of Formants one and two (F1 and F2), and sound pressure level (SPL) in eight neurologically healthy women with no speech, language, voice or hearing impairments. The subjects were instructed to read aloud 24 sentences beginning and ending with target words containing a corner vowel (/i/, /a/, /u/ or /æ/) or a diphthong (/aɪ/ or /oi/) at three lung volume levels: 40% of vital capacity (low level), 60% of vital capacity (typical level), and 80% of vital capacity (high level). Vowel duration was not found to be affected by lung volume. However, both F0 and SPL increased as the lung volume increased. The authors concluded that phonatory and articulatory behaviour can be manipulated by the modification of the respiration system via changes of lung volume.

These findings were consistent with the results reported by Dromey and Ramig (1998), who examined the effect of lung volume on phonation and articulation in 5 male (mean age = 31 years) and 5 female (mean age = 32 years) native English speakers. The subjects were instructed to repeat aloud a short sentence containing the syllable /pæp/ in word medial position ten times at five different levels of lung volume: habitual level, immediately after maximum inhalation, maximum inhalation (while maintaining normal speech), low level, and end of expiratory level (i.e. after a sigh). The authors reported that both F0 and SPL increased as the lung volume increased but the effect of lung volume on lip and jaw displacements remained unclear.

Speech breathing in children with dysarthria secondary to CP has also been studied. Hardy (1961) observed the intraoral pressure of a girl at four years of age during a maximal phonation task and found that the subject's intraoral pressure was smaller (26 cm/H_2O) than most of the neurologically healthy children (35 cm/H_20) as reported in Goddard's study in 1959 (cited in Hardy, 1961). Hardy (1967) further investigated the maximum oral pressure during a maximal phonation task performed by two 12-year-old girls, including a neurologically health girl and a girl with severe dysarthria secondary to spastic quadriplegia, and reported the maximum oral pressure generated at 70% vital capacity for the former was 50 cmH_2O and the latter 20 cmH_2O. These findings indicated that a lack of strength in the respiratory muscles would lead compromised respiratory function. The mean vital capacity of children with spastic and athetoid CP were found to be lower than neurologically healthy controls with the same height. In addition, both rest breathing and speech breathing were found to be less problematic in children with spastic CP than children with athetoid CP (Hardy, 1983).

In summary, speech breathing requires fine motor coordination between respiratory and speech musculatures. Speakers with dysarthria have been shown to exhibit compromised speech breathing, including reduced vital capacity, inefficient use of lung volume, and increased weakness of respiratory muscles leading to problematic phrasing and loudness control.

1.2.2.2 Therapeutic Approaches Related to Breath Control

In speech therapy, there are three main approaches: physiological, behavioural, and pragmatics (Adams, 1997; Murdoch 1998). In treating speech of individuals with CP, physiological therapy is mainly focused on improvement of breath control through posture management and the implementation of various facilitating strategies, such as overarticulation, proper phrasing and pacing, and breathing exercises.

1.2.2.2.1 Overarticulation

Overarticulation, also known as "exaggerating consonants", is a traditional treatment technique where patients learn to articulate all consonant phonemes in a precise manner (Freed, 2000). Overarticulation, defined as "purposeful, exaggerated articulation of consonant phonemes" (Freed, 2000), is considered to be useful for improving speech intelligibility.

Individuals with dysarthria are often instructed to increase articulatory effort and reduce speech rate to facilitate efforts aiming for exaggeration (Duffy, 1995). In particular, it has been proposed that individuals with dysarthria should focus on clear pronunciation of medial and final consonants, which are most often articulated poorly in connected speech. In cases of flaccid dysarthria, marked improvement on speech intelligibility has been observed when medial and final consonants were fully articulated (Netsell & Rosenbek, 1985; Darley, Aronson, & Brown, 1975). However, there are limited empirical data concerning the efficacy of overarticulation as a behavioural strategy.

Indirect evidence showing the usefulness of "overarticulation" in improving speech intelligibility has been shown through studies of individuals with other speech difficulties. Searl and Carpenter (2002) investigated the usefulness of four acoustic measurements, including voice onset time (VOT), duration of the preceding vowel, and the duration and SPL of the consonant, for differentiating the production of voiced and voiceless consonants by 16 tracheoesophageal speakers from those by ten age-matched laryngeal speakers. Each speaker produced, in one breath, the carrier phrase containing one of the ten nonsense words with a voiced or voiceless plosive and fricative, which were prompted through both written and verbal forms. Consonant length, vowel duration, and SPL were found to be most useful for differentiating the speech of the tracheoesophgeal speakers from that of the laryngeal speakers, with tracheoespphageal speech being associated with prolonged consonant and vowel durations. This finding was consistent with the finding from previous studies that laryngeal speakers produced longer consonants and vowels when attempting to increase articulatory precision (Gordon-Salant, 1986; Pinchey, Durlach, & Braida, 1983). Although the impact of overarticulation on speech intelligibility was not examined in these studies, it has been shown that speakers, with or without prompting, are likely to either adopt a slower rate of speech or articulate in a more precise manner in attempting to improve speech intelligibility (Searl & Carpenter, 2002). Since speech rate depends on the frequency of air replenishment in connected speech, reduction of speech rate may be related to shortening of a breath group.

1.2.2.2.2 Proper Phrasing and Pacing

As previously mentioned, speakers with dysarthria secondary to CP often have difficulties phrasing their speech due to poor speech breathing (Yunusova et al., 2005). Speech therapy for this population often includes phrasing and pacing as strategies to enhance breath control. A breath group, defined as an utterance "produced on one continuous interval of expiratory flow" (Weismer, 2007), may continue for approximately 150 milliseconds or longer, between two inter-word pauses with inhalation (Tsao & Weismer, 1997).

A number of studies have shown the relationship between the length of breath group and speech intelligibility in speakers with dysarthria (e.g., Wang, Kent, Duffy & Thomas, 2005). Wang et al. (2005) investigated the breath group structure and various aspects of prosodic features in the conversational and sentence speech samples obtained from 12 individuals with dysarthria secondary to traumatic brain injury (TBI). The authors found that the TBI group had more inappropriate breath location and pause proportions, in particular, more variable pauses between breath groups, as compared with eight control participants. In addition, the length of a breath group was found to be more reduced and less variable in individuals with severe TBI than those with mild TBI and the control participants. Prosodic disturbance also appeared to be more common with the TBI group, with a difference in the degree of disturbance between the mild and severe groups. This finding showed that breath group was often compromised in speakers with dysarthria. Therefore, breath group training may be a relevant treatment technique in speech therapy for this population.

In a study of breath group and speech intelligibility in ten speakers with dysarthria, the number of words per breath group was found useful for predicting the speech intelligibility for the moderately intelligible speakers with dysarthria (Yunusova et al., 2005). Specifically, speech intelligibility for speakers whose intelligibility was affected moderately was found to increase as the number of words per breath group increased. However, this relationship was reversed for the two most intelligible speakers with dysarthria. Furthermore, the measure of the number of words per breath group was not found useful for differentiating control speakers from speakers with dysarthria. These findings suggested that changes in the length of a breath group affected speech intelligibility differently depending on the severity of the speakers' speech impairment.

In summary, some research findings have shown the usefulness of proper phrasing and pacing for enhancing speech intelligibility, especially for those with more severe dysarthria. Although the phrasing and pacing technique has been employed to improve speech intelligibility for speakers with dysarthria (Yunusova et al., 2005; Wang et al., 2005), instrumental studies on how the length of a breath group may impact on the articulatory and laryngeal behaviors as well as the acoustic output in the CP population are still needed to provide empirical evidence needed for better clinical management.

1.2.2.2.3 Breathing Exercise

As mentioned earlier, respiratory support in individuals with CP is often compromised, as reflected in a decrease in vital capacity. Therefore, therapy for this population includes strengthening exercises to increase vital capacity. It was indicated that, given an adequate laryngeal, velopharyngeal, and upper articulator valving function, these exercises may lead to the lengthening of breath group (Solomon & Charron, 1998). Although breathing exercises have been employed to strengthen the respiratory muscles, only limited evidences were available to assess their treatment efficacy (Solomon & Charron, 1998). Nevertheless, the usefulness of these breathing exercises for improving vital capacity has been shown. For example, Rothman (1978) investigated the effects of non-speech respiratory strengthening exercises on vital capacity and the forced expiratory volume as measured by a spirometer before and after treatment. Subjects in this study included ten children with spastic CP. The five subjects assigned to the control group received no treatment while the rest of the subjects were assigned to the experimental group participating, for eight weeks, in breathing exercises designed to strengthen both inspiratory and expiratory muscles. Each exercising session, which lasted for approximately five to seven minutes long, included blowing, abdominal strengthening, and breathing with and without resistance. The experimental group also learnt to inhibit abnormal breathing behaviors. Results from data obtained both before and after treatment revealed that forced expiratory volumes for all children were within normal limits. However, before treatment, vital capacity was reduced in all subjects when compared to the normal predicted data. After treatment, the average vital capacity of subjects who received respiratory exercises was found to have increased by 31% while children who did not participate in the exercising program showed no change. However, the effect of breathing training on speech was not studied. Therefore, further investigation on the speech effect of therapeutic strategies related to breath control is needed.

The incoordination of the breathing musculatures in speakers with dysarthria has received some attention in the literature (Netsell & Hixon, 1992). Netsell and Hixon (1992), in a study of patients with moderate dysarthria secondary to TBI, employed the “inspiratory checking” technique, where speakers were asked to inhale deeply and exhale slowly during speech production, found the technique to be useful for three out of six participants. In a more recent study conducted by Cerny, Panzarella, and Stathopoulos (1997), children with respiratory hypotonia, following a six week exercise program (15 minutes per day) focusing on strengthening the expiratory muscles through use of a face mask as a resistance against the expiratory airstream, were found to have increased SPL and subglottal pressure at habitual and loud speech. As CP might involve not only respiratory hypotonicity but also a combination of other types of aberrant tonicity or control problems, this finding of treatment effect may not be readily generalized to individuals with CP. The potential benefit of breath control training on the speech production of the CP population needs to be confirmed with studies of speech measurement in this population.

1.2.3 Speech Measurement

Speech measurement in dysarthria may be physiologically, perceptually or acoustically based.

1.2.3.1 Measurement of Articulatory Movement

Disturbances in articulatory coordination of the lips, tongue, mandible, and velum in individuals with cerebellar dysfuntions have been reported (Kent et al., 1978). Kent et al. (1978) examined the speech of five adult speakers with ataxic dysarthria secondary to cerebellar diseases, including ideopathic cerebellar degeneration. The speakers performed a series of speech tasks, including repetitions of 30 sentences, eight monosyllabic (CVC) words, 16 multisyllabic words (two or three syllables), and three minutes of spontaneous connected speech, and two oral motor tasks, including repetition of the /pa/ trains and counting from one to twenty. Acoustic analysis revealed that syllable segments were consistently longer for these individuals than for neurologically healthy speakers. The length of segments also increased as the severity of dysarthria worsened.

Shaiman, Adams, and Kimelman (1995) studied changes in the temporal relationships of the upper lip and jaw in response to the manipulation of vocal rate in eight neurological healthy individuals and found these changes to be speaker specific. Shaiman (2001) investigated the effect of temporal control of the upper lip and jaw displacements as a function of speech rate and phonetic context. She instructed five adult female subjects to repeat three nonsense words, each in a short carrier phrase, 30 times at three rates: habitual, fast (double the rate in habitual condition), and slow (half the rate in habitual condition). Upper lip and jaw displacements values were collected via a head-mounted strain gauge transduction system. Consistent with the findings in Shaiman et al.'s study (1995), it was found that the temporal relationship between the upper lip and jaw varied across individuals. McClean and Tasko (2003) employed electromyographic (EMG) measurements to study the relationship between movements of the orofacial muscles and variations in speech intensity and rate in three neurologically healthy adults. They found that the EMG levels of the mentalis, depressor labii inferior, anterior belly of the digastric, and masseter muscles were all positively correlated with intensity but inversely correlated with speech rate. These findings suggested that articulatory movement was affected by the control mechanism for loudness and speech rate, which may be related to respiratory control.

1.2.3.2 Acoustic Analyses of Dysarthric Speech

Perceptual assessments are practical in classifying types of dysarthria and can provide valuable information for understanding the relationship between production and perception (Hustad, 2006). However, the reliability of perceptual measures may depend on the level of intersubject or intrasubject variability (Kent et al. 1992). Therefore, acoustic analyses have been used to complement perceptual evaluations in the assessment and diagnosis of dysarthria. The acoustic-perceptual approach is a useful method to identify acoustic and perceptual alterations reflecting aspects of speech intelligibility in dysarthric speech (Kent et al., 1992). Acoustic measures, such as vowel onset time, vowel duration, and vowel formant frequencies, add objectivity to the judging process and are generally advised to complement perceptual analysis (Collins, 1984). A number of acoustic measurements can be undertaken with dysarthric speech.

1.2.3.2.1 Voice Onset Time

Voice onset time (VOT) is commonly employed for the differentiation of voiced and voiceless plosives. Voice onset time, typically measured as the interval between the release of the burst of air for the consonant to the onset of the first glottal cycle for voicing of the following vowel (Lisker and Abramson, 1964, 1967), reflects the coordination of the orolayngeal system. Studies have investigated the relationship between VOT and various parameters such as consonant contexts and vowel duration.

In a study examining the relationship between VOT and vowel duration, Port and Rotunno (1979) instructed five neurologically healthy native speakers of American English (one male and four females) to read a list of words made up of /p/, /t/, /k/ and six vowels (three corner vowels and three lax vowels). The results indicated that VOT was positively correlated with vowel duration.

In a similar study, Hoit, Solomon and Hixon (1993) investigated the relationship between VOT and lung volume in five neurologically healthy native American English male speakers between the age 20 to 24. Each subject was instructed to repeat, following maximal breath intake, a short phrase consisting of six syllables in their habitual pitch and loudness while standing. The syllable /pi/ was included and stressed in the second and fifth syllable and the rate of speech was monitored using a metronome. Measures of VOT were estimated, using hard copies of the spectrograms, as the period between the beginning of the burst of noise and the beginning of the second formant frequency. Results from the simultaneous recording of speech and surface motion of the chest revealed that the duration for VOT was partly dependent upon the lung volume. Hoit et al. (1993) proposed that the tendency for VOT to increase with an increase in lung volume was most likely due to a "tracheal tug" and the tendency for VOT to decrease with reduced lung volume was related to the need to save air.

Farmer (1980) examined VOT on phonetically balanced words articulated by five athetoid and five spastic CP speakers English by spectrographic analysis. The chosen words all began with either a voiced (/b/, /d/ and /g/) or voiceless (/p/, /t/ and /k/) plosive. Farmer (1980) reported that VOT values in /p/, /t/ and /g/ were significantly longer and more variable in speakers with athetoid CP than those in speakers with spastics CP. Ansel & Kent (1992) examined monosyllabic (CVC) minimal pairs of real words produced by 16 men with dysarthria secondary to mixed CP and found through spectrographic analysis that VOT for voiceless stops ranged from 16 ms to 272 ms, with a mean of 95.3 ms. Findings from the aforementioned studies suggest that VOT measures would be useful for monitoring changes in respiratory support or speech production effort.

1.2.3.2.2 Diadochokinetic Rate

The rate of oral diadochokinesis (DDK), defined as the rate of maximally rapid syllable repetition, is a standard component of motor speech assessment (Darley et al., 1975; Duffy, 1995; Enderby 1983; Yorkston, Beukelman, Strand & Bell, 1999). The task used to derive oral DDK rate is a speech-like task involving rapid monosyllabic repetitions of real English syllables, such as /pə/, /tə/, /kə/, or /bə/, /də/, /gə/ (Hixon & Hardy, 1994; Kent, 1997). The type of rapid repetition of syllable sequences is referred to as alternating motion rate (AMR), as opposed to sequential motion rate (SMR), defined as rapid repetition of a single syllable, such as /pə/ (Darley et al., 1975; Duffy, 1995). Oral DDK requires a prompt exchange between the reciprocal innervation pattern of the agonists and antagonists required for speech production and thus oral DDK rate is considered useful for the differential diagnosis of dysarthria and other neurologic diseases as well as for determining the severity of speech motor control impairments (Darley et al., 1975; Duffy, 1995). Global, segmental timing of DDK as well as temporal regularity has been quantified in individuals with dysarthria (Kent, Duffy, Kent, Vorperian & Thomas, 1999; Ackermann & Ziegler, 1991; Ackermann, Hertich & Hehr, 1995). Energy characteristics for DDK tasks have also been described for speakers with dysarthria but have been examined less thoroughly than temporal characteristics of DDK.

Inaccurate and inconsistent oral DDK performances are frequently observed in individuals with motor speech disorders (Duffy, 1995). Studies have been conducted in adults and children with dysrathria secondary to CP (Hixon & Hardy, 1964; Platt, Andrews, Young & Quinn, 1980; Schiliesser, 1982) and patients with stroke (Kent et al., 1999), amyotrophic lateral sclerosis (Ziegler, 2001), traumatic brain injury (Wang, Kent, Duffy, Thomas, Weismer, 2004), or Parkinson's disease (Tjaden & Watling, 2003; Ziegler, 2001). Wang et al. (2004), in comparing the DDK rates for /pa/, /ta/, /ka/, /da/, and /sa/ between a group of seven adults with TBI induced dysarthria and five control adults, found that the mean DDK rate for the TBI group (mean = 3) was approximately 2.5 syllable per second slower than the mean DDK rate for the control group (mean = 6.5). The authors also reported that the groups with the highest and lowest DDK rates were the groups with the lowest and the highest severity levels respectively.

Platt et al. (1980) examined speech obtained from 50 males with CP (32 spastic type and 13 athetoid type) between 17 to 55 years of age while reading 50 monosyllabic words, followed by the *Grandfather* passage, and finally, syllable repetition in ten seconds-segments. The perceptual measures of articulation employed in this study included speech intelligibility ratings of single words and connected speech by fifty listeners, phonetic transcription for articulation accuracy, and DDK rates for the extent of articulatory impairment. Platt et al. (1980) reported the average DDK rate for all CP subjects was 2.9 syllable per second (SD = 1.3), which half of was expected for neurologically healthy adults. Specifically, the mean DDK rate for speakers with spastic CP was 3.4 syllable per second (SD = 1.2), which was significantly higher than the two syllable per second (SD = 0.7) shown in the athetoid group. Platt et al. (1980) suggested the differences in DDR between the two groups were likely to be related to the fact that individuals in the spastic group were less physically impaired than those in the athetoid group. Overall, the reduction in DDK rate reported in speakers with CP indicates that orolayngeal coordination is problematic in this population.

While time-based measurement in acoustic analysis provides information regarding the coordination of speech musculatures, frequency-based measurement has been found to be useful for reflecting tongue movement or vocal tract configuration as well as for the study of speech intelligibility.

1.2.4 Vowel Working Space

Acoustic signals provide a link between the production and perception of speech in that it not only reflects vocal tract configuration and voicing properties but also serves as the object of speech perception. It has been found that the first two formant frequencies were dependent on tongue height and advancement, with F1 increasing as the tongue height decreases and F2 decreasing as the tongue moves more backward (Kent, et al., 1999). The F1-F2 plot, also known as a vowel plane/space/area/ quadrilateral, is often used to represent the working space for vowel production as well as the perceptual space for vowel differentiation (Peterson & Barney, 1952). While some studies have reported the use of vowel working space as an acoustic measurement of vowel articulation, other studies have examined the relationship between vowel working space and speech intelligibility (e.g., Liu, Tsao, & Kuhl, 2005; Tjaden, Rivera, Wilding & Turner, 2005; Turner, Tjaden, & Weismer, 1995; Ziegler & von Cramon, 1983).

1.2.4.1 Relationship between Vowel Working Space and Articulatory Movement

Vowel working space is commonly employed to quantify the precision of vowel articulation and examine the gross motor control ability of the tongue and jaw co-ordination (Kent et al., 1999; Liu et al., 2005). The vowels, /i/, /a/, /u/, /æ/, are often chosen for investigation of an individual's vowel working space (e.g., Fourakis, 1991; Krause & Braida, 2004; Liu et al., 2005; Ziegler & von Cramon, 1983) because these vowels, often referred to as corner vowels, are characterized by their extreme F1 and F2 frequencies representing the limits of a vowel working space (Lindblom, 1990). These corner vowels are also the most common vowels amongst all the spoken languages (Ladefoged & Maddieson, 1996).

The area of the vowel working space has been found to be affected by speech rate. Several studies have shown the effect of speech rate on vowel working space in the speech of neurologically healthy adults (e.g. Fourakis, 1991; Krause & Braida, 2004; Picheny, Durlach, & Braida, 1986; Ziegler & von Cramon, 1983) and speakers with dysarthria (Tsao, Weismer & Iqbal, 2006; Turner et al. 1995).

Fourakis (1991) investigated nine English vowels, including the corner vowels, in eight neurologically intact speakers and found that the vowels articulated in the slow stress condition and fast unstressed condition resulted in the largest and smallest vowel working space respectively, with the latter being approximately two thirds of the size of the former. Specifically, it was found that the corner vowels /a/ and /u/, and the lax vowels /ɔ/, /ʊ/ and /ʌ/ contributed to the majority of the reduction in the vowel working space (Fourakis, 1991).

Similarly, Turner et al. (1995) studied the effect of vowel working space as a function of speech rate in nine adults (four females and five males) with amyotrophic lateral sclerosis (ALS) induced dysarthria and nine age and gender matched controls. All subjects read aloud the Farm Passage (Crystal & House, 1982; Turner et al., 1995) in habitual, fast (double the habitual rate) and slow (half the habitual rate) conditions. Vowel formant frequencies were obtained from 79 monosyllabic words from the Farm Passage (Crystal & House, 1982; Turner et al., 1995) containing one of the four corner vowels /i/, /a/, /u/, or /æ/. Speakers with ALS generally showed a more restricted vowel space than the controls. Although both groups demonstrated an inverse relationship between vowel space and speaking rate, the trend was less obvious for the ALS group than for the control group.

Vowel working space has also been widely reported in studies of dysarthric speech (Tjaden et al., 2005; Ziegler & von Cramon, 1983). In an early study by Ziegler and von Cramon (1983), measurements of the vowel space area of speakers with dysarthria secondary to close head trauma during the period of natural recovery revealed that the size of the vowel space increased as articulatory precision increased. A positive correlation between speech intelligibility and the area of the corner vowel space has also been shown in Mandarin and Cantonese speakers with dysarthria (Liu et al., 2005; Whitehill & Ciocca, 2000).

While the majority of research on vowel working space examines the English corner vowels of /i/, /a/, and /u/, Tjaden et al. (2005) investigated the English lax vowels of /ɪ/, /ɛ/, and /ʌ/. Lax vowels have less extreme formants and require reduced vocal tract shapes relative to corner vowels. Tjaden et al. (2005) reported no consistent changes for lax vowel space areas for the speakers with dysarthria during connect speech at a reduced rate. This finding questions the common clinical assumption that rate reduction may improve the speech of individuals with dysarthria.

In addition, Tjaden et al. (2005) also found that there were no difference between the vowel space area in the Parkinson’s disease group and the control group, whereas the vowel space area in the amyotrophic lateral sclerosis (ALS) group was 50% less that the control group. This finding suggested that both pathophysiology and overall severity might have contributed to the between-group differences.

Based on these findings, it is apparent that the area of vowel working space is sensitive to articulatory changes resulted from change of speech rate or various neurological disorders. Further investigation regarding the acoustic-articulatory relationship in CP speech is needed to assess the efficacy of treatment focusing on increasing respiratory control, which is commonly chosen for this population.

1.2.4.2 Relationship between Vowel Working Space and Speech Intelligibility

The positive relationship between vowel working space and speech intelligibility has been shown in both neurologically healthy speakers and speakers of speech impairment. For example, it has been found that neurologically healthy speakers with smaller vowel working spaces were judged to be less intelligible than those with larger ones (Bradlow, Torretta, & Pisoni, 1996; Fourakis, 1991). It has also been shown that clear speech spoken at normal speed was associated with larger vowel working space than those spoken in conversational speech (Krause & Braida, 2004). Decreased speech intelligibility has been associated with a reduction in the corner vowel space in speakers with dysarthria secondary to traumatic brain injury (Ziegler & von Cramon, 1983), Parkinson’s disease (Tjaden & Wilding, 2004; Weismer, Laures, Jeng, Kent & Kent, 2001), ALS (Tjaden, et al., 2005; Turner et al., 1995; Weismer et al., 2000, 2001; Weismer, Martin, Kent & Kent, 1992) and other pathologies (Higgins & Hodge, 2002) as well as individuals with glossectomy (Whitehill, Ciocca, Chan & Samman, 2006).

In a recent vowel production study by Higgins and Hodge (2002), children with dysarthria were found to exhibit a smaller vowel space in comparison to the neurologically healthy controls. Furthermore, the corner vowel space was found to be positively correlated with the single word and sentence intelligibility test scores. Similar results were found for individuals with dysarthria secondary to CP (Liu et al., 2005). Liu et al. (2005) examined the relationship between vowel working space and speech intelligibility in single words spoken by 20 young Mandarin-speaking CP adults and ten age and gender matched control adults. The results revealed a shrunken corner vowel spaces as well as lower speech intelligibility scores in the CP group. The CP adults were found to display a significantly lower F1 value of the low vowel /a/ and a significantly higher F1 value of the high vowel /i/ as compared with the neurologically healthy controls. Since F1 variations could be related to the tongue height during vowel production, this finding was interpreted as indicating a restriction in vertical movements of the jaw and tongue of participants with CP. Similarly, the range of F2-F1 values for the front-back vowel contrast was found to be significantly narrower for participants with CP as compared to neurologically healthy controls.

In summary, these studies have demonstrated that vowel working space is positively correlated with speech intelligibility of individuals with and without dysarthria. However, there is a paucity of instrumental studies investigating the speech of New Zealand English speakers with CP.

1.3 Research Question

1.3.1 Purpose and Importance of the Study

There have been limited studies examining the effect of breath group control upon speech production in individuals with dysarthria associated with CP. On this basis, the current study employed a simultaneous acoustic, electroglottographic (EGG), and marker-based facial tracking recording system to investigate the effect of breath group control on the speech production behaviors of individuals with CP and healthy controls. The instrumental measurement included in this study will provide scientific evidence useful not only for evaluating the effectiveness of a commonly used speech therapy strategy but also for understanding how oral-laryngeal coordination may be maintained by individuals with CP in comparison with neurologically healthy speakers in response to different levels of task complexity. Since some speech breathing treatment have been found useful for speech enhancement, it is possible that an improved understanding of articulatory-phonatory coordination will result in the development of improved intervention techniques for speakers with dysarthria with CP and possibly individuals with the type of speech or voice impairment exhibiting a similar breakdown of oral-laryngeal coordination.

1.3.2 Aims and Hypotheses

The purpose of this study is to examine how breath group control, a therapeutic technique commonly used for speech enhancement, may improve the articulatory and laryngeal movement as well as the acoustic features related to speech intelligibility. Main questions regarding the effect of breath group control include:

1. **Is there an effect of breath group control on jaw displacement, phonatory stability, and articulatory movement (or vowel space)?**

   Based on the common usage of the breath group control strategy in speech and voice therapy and some findings of a positive relationship between vowel space and speech intelligibility in the literature as previously discussed, it is hypothesized that breath group control would result in greater extent of jaw displacement, increased phonatory stability, and expanded vowel space in both non-speech and connected speech tasks. Specifically, it is hypothesized that:

   a. In connected speech task, productions with breath group cueing will exhibit shorter voice onset time, larger vowel space, and increase in phonatory stability as compared with those without breath group cueing.
   b. In non-speech task, productions with a shorter breath group will be associated with shorter voice onset time, larger vowel space, and increase in phonatory stability and maximum jaw displacement.

2. **Does the positioning of a speech production in a breath group affect articulatory movement and phonatory stability?**

   It is hypothesized that the articulatory movement and phonatory stability will vary by the positioning of a speech production in a long multisyllabic utterance. In particular, it is hypothesized that vowels in the first position of a long breath group will be associated with shorter voice onset time, larger vowel space, and increase in phonatory stability as compared with those in the last position of the utterance.

3. **Does the place of articulation of the consonant have an effect on the extent of jaw displacement as well as articulatory movement and phonatory stability?**

   It is hypothesized that the place of articulation of a consonant has an effect on the extent of jaw displacement as well as articulatory movement and phonatory stability. Specifically, it is hypothesized that:

   a. The place of articulation of the consonant has an effect on the extent of jaw displacement and articulatory movement, with bilabial voiceless plosive resulting in larger jaw displacements because of minimal tongue involvement.

   b. The place of articulation of the consonant has minimal effects on the vibrating frequency of the vocal folds but may affect the vocal fold vibratory pattern and phonatory stability due to the physical linkage between the tongue and the larynx.

4. **Does breath group control affect the control and CP groups differently?**

   It is hypothesized that the CP group would generally demonstrate more restricted articulatory movements and poorer articulatory and phonatory stability than the control group. The effect of breath group control would be more evident in the CP group while the effect shown in the control group may be minimal due to a ceiling effect.

Chapter 2. Methodology

2.1 Participants

A convenience sampling method was used for subject recruitment. Ethical approval was obtained from the institutional ethics review committee prior to the expeirment. Advertisement was posted around the Univeristy of Canterbury campus and the Christchurch public library to recruit meurologically healthy adults. Volunteering adults were included as controls in the study if they met the following criteria: no previous history of speech, hearing, or neurological disorders, no surgery performed on the head and neck, and no observable speech and voice abnormality on the day of recording. An invitation letter was sent to the New Zealand Crippled Children Society (CCS) via email to recruit adults with CP. For the CP group, subject inclusion criteria included: a medical diagnosis of CP, a speech and langage therapy diagnosis of dysarthria, adequate English speaking proficiency, and adequate hearing, vision, and cognitive capability to comprehend and execute the experimental tasks.

The control group consisted of eight males and eight females, aged between 21 and 50 years, with a mean of 32.1 years (SD = 9.5) for males and 29.5 years (SD = 7.9) for females (see Appendix 1). The CP group consisted of three male and one female native speakers of New Zealand English, ranged in age from 19 to 42 years. Subjecct information for the CP group was shown in Table 1.

2.2 Materials

The experimental stimuli included a non-speech syllable production task and a connected speech task. The non-speech task included production of a consonant-vowel (CV) syllable under three experimental conditions. The three conditions were (i) production of a CV syllable in one breath, (ii) three repetitions of the CV syllable in one breath, and (iii) five repetitions of the CV syllable in one breath. The consonants included were /p/, /t/ and /k/ and the vowels included were /i/, /a/, /u/ and /ɔ/. The three consonants were included because they differed only in place of articulation, allowing for a comparison between articulations with different degrees of tongue advancement and elevation. The three corner vowels /i/, /a/, and /u/ were included because they were vowels requiring the tongue shape to be formed at the extreme positions in the oral tract. The vowel /ɔ/ was included because the vowel /u/ in modern New Zealand English has been found to be fronted (Watson et al., 1998, Gordon et al, 2004; MacLagan et al., 2005; MacLagan & Hay, 2007) and thus might not meet the definition of corner vowel as well as /ɔ/. Each CV combination was repeated in five trials. In total, there were 180 (3 consonants X 4 vowels X 3 breath group types X 5 trials) tokens. All tokens were presented in a predetermined random order.

The connected speech task comprised a reading passage that contained 30 words, eight of which consisted of one of the four corner vowels targeted (i.e. /i/, /a/, /u/, and /ɔ/). The passage was “Last time the lid was loose and the soup I bought leaked all over my bag. I started cleaning it as soon as I could. I thought I did my best to save my bag.” Two forms of the passage were used, one with and the other without marking and word arrangement cueing for proper phrasing.

2.3 Instructions to Participants

The reading stimuli were presented in written forms on bound pages placed on a music stand in front of the participant to elicit the corresponding speech production. Prior to performing the non-speech task, the participant was instructed to repeat five times the reading passage without any forms of breath group cueing. During the non-speech task, the participant was instructed to read each of the 180 monosyllabic or multisyllabic nonsense words. After the non-speech task, participants were instructed to repeat five times the reading passage presented with breath group cueing. For both non-speech and connected speech tasks, participants were given verbal instructions and demonstration on what was required to perform the task.

2.4 Instrumentation

The recording instruments included the acoustic, electroglottographic, and marker-based facial tracking devices. A schematic illustration of the instrumentation setup was shown in Figure 1. The acoustic recording system consisted of a headset microphone (AKG C420, Austria) and a mixer (Eurorack MX602A, Behringer) used as microphone preamplifier. The electroglottography (Kay Elemetrics Model 6103, USA) consisted of a connector box and two electrodes, each with a diameter of 3.5cm. The video facial tracking system consisted of a mini-camera (1/4"CMOS PC camera, Taiwan) equipped with the capacity to emit infrared light on the two sides of the lens. Eight dots, each with a diameter of 6 mm, were cut out of a reflective material. Four dots were attached to the centre of the borders of a cardboard piece (4 cm X 4 cm), which was attached to the center of the subject's forehead for calibration purpose. The remaining four dots were placed on the participant's nose tip, chin (in the vicinity of mandibular symphysis), and the right and left-hand sides at the corners of the lips.

For simultaneous recordings of the acoustic and EGG signals, the output of the mixer and the output of the EGG device were connected to separate channels of a 12-bit A/D converter (National Instrument DAQCard-AI-16E-4, USA) via a SCB-68 68-pin shielded connector box. The connector box contained a filter for each channel, with acoustic signals low-passed at 20 KHz and EGG signals at 5 KHz. The A/D converter was housed by a laptop computer (Compaq 650 MHz Pentium 4, Taiwan) for direct digitization. For recordings of the marker-based facial tracking signals, the output of the mini-camera was connected to the USB port of a second laptop (Acer, Taiwan) installed with a locally developed program written in the C+ language.

For data analysis, a locally developed algorithm written in MATLAB 7.0 (The Mathworks, Inc., USA) was used to process EGG and facial tracking signals and a time-frequency analysis software (TF32; copyright: Paul Milenkovic, 2000, USA) was used to perform analysis of the acoustic signals.

2.5 Procedure

Subjects were seated in a quiet laboratory room where noise level was monitored to be no higher than 40 dB SPL. With the instrument in place, participants were instructed to perform the experimental tasks as previously described. The connected speech task without cueing on breath control was performed first, followed in order by the non-speech CV production task and the connected speech task with cueing on breath control. A two-minute break was taken approximately every 15 minutes, during which subjects were encouraged to have a voice rest and a drink of water. Each session lasted for approximately 60 to 90 minutes.

2.6 Measurements

Experimental measures were derived from acoustic, EGG, and facial tracking signals separately.

2.6.1 Acoustic Measurements

Acoustic measurements included VOT, vowel duration, vowel formant frequencies (i.e. F1 and F2), and F0. Voice-onset time was included in this study as it is frequently used to distinguish between voiced and voiceless plosives (Ladefoged, 1975) and to measure oral-laryngeal coordination (Kent et al.1999). Percent jitter (%jitter), percent shimmer (%shimmer), and signal-to-noise ratio (SNR) were included to reflect phonatory stability (Gelfer, 1995). The formant frequencies were included to reflect the degree of tongue elevation and advancement, with a higher F1 indicating a lower tongue position (Monsen, 1976) or a higher degree of pharyngeal constriction (Baken & Orlikoff, 2000) and a higher F2 a more forward tongue placement or a lower degree of posterior oral constriction (Baken & Orlikoff, 2000). Based on the F1 and F2 values of vowels /i/, /a/, and /u/ or /i/, /a/, and /ɔ/, the area of the vowel space (i.e., vowel triangle) was calculated. All vowel working spaces were calculated using the following formulae from Liu et al. (2005):

“Vowel space area = $ABS\{[F1i*(F2a-F2u)+F1a*(F2u-F2i)+F1u*(F2i-F2a)]/2\}$ where ABS is absolute value, F1i symbolizes the F1 value of vowel/i/, and so on.”

2.6.2 Electroglottographic Measurements

Three measures were obtained from EGG signals: F0, speed quotient (SQ) and open quotient (OQ). The F0 obtained from the EGG signals was employed as a comparison against the F0 derived from the acoustic signals. The temporal measures SQ, defined as the ratio between opening phase and closing phase, and OQ, defined as the ratio between open phase and cycle period, were used to reflect glottal efficiency and the degree of vocal fold abduction respectively. A 90% method was used to define various phases during a glottal cycle, with the time between 10 and 90% of the whole amplitude range of a glottal cycle during glottal opening defined as the opening phase, that during glottal closing the closing phase, and the time between the two 90% points the open phase (Lim et al., 2006).

2.6.3 Facial Tracking Measurements

The facial tracking signals were used to yield measures of maximum jaw displacement. Figure 2 shows a display of the tracings for lip spreading and jaw opening in the recorded signal, with time on the X-axis and amplitude on the Y-axis.

The tracing for lip spreading represents changes of the distance between the dots on the two sides of the mouth, with a higher value indicating a larger degree of lip spreading. The tracing for jaw opening represents changes of the distance between the dots on the chin and on the nose, with a higher value indicating a larger degree of jaw opening. During recording, the displacement values had been automatically calibrated in the computer algorithm using values of the reference dots placed on the forehead and thus the displacement values represented real-size readings in millimeters rather than pixel values.

2.7 Data Analysis

Acoustic and EGG measures were derived from the monosyllabic utterance (labelled as “p1”) and the initial and final syllables of a 3-syllable (“P3-1” and “P3-last” respectively) or 5-syllable (“P5-1” and “P5-last” respectively) utterance. Measures of maximum jaw opening were extracted from the facial tracking signals for the monosyllabic utterance (“1-syllable”) and the two multisyllabic utterances (“3-syllable” and “5-syllable”). Acoustic, EGG, and facial tracking measures obtained from the non-speech task, and the acoustic measure of vowel formant frequencies from the connected speech were analyzed

2.7.1 Acoustic Analysis

Acoustic measurements were obtained using TF32 (a time-frequency analysis software; copyright: Paul Milenkovic, 2000, USA). For measures of VOT, the time waveforms and spectrogram of the acoustic signals were displayed on the computer screen and the experimenter cursor-selected the period between the release of the stop burst and the onset of voicing. Vowel duration was measured as the period between the onset of voicing and the first glottal pulse. Vowel formant frequencies were located using the linear prediction coding (LPC) spectra. Measures of F1 and F2 frequencies were obtained by placing the cursor at the midpoint of each vowel segment. In cases where vocal irregularities affected the clarity of the site of vowel formants, the cursor was moved until the formants were clearly visible. Fundamental frequency, percent jitter (%jitter) and percent shimmer (%shimmer), and signal-to-noise ratio (SNR) data were extracted by selecting a segment of approximately 100 ms (+/– 5ms) from the mid-section of the vowel using the time waveform display.

2.7.2 Electroglottographic Analysis

All EGG measurements were obtained from a locally developed algorithm written in MATLAB 7.0 (The Mathworks, Inc., USA). Upon viewing of the time waveforms of the EGG signals, a segment of 5,000 ms from the target syllable were selected for analysis. On the occasions where a segment of 5,000 ms could not be determined due to vocal irregularities or poor EGG signals, a minimum of 3,000 ms was used for analysis.

2.7.3 Facial Tracking Analysis

To derive the extent of jaw opening during single and repeated CV production, the experimenter displayed the recorded signals on the computer screen and wrote down the cursor values for the peak of the jaw tracing during the vowel segment (as can be verified with the presence of a simultaneous excursion of the extent of the lip spreading) and for the baseline of the jaw movement indicating the jaw at rest. The values were entered into a spreadsheet for automatic calculation of the extent of jaw opening, which was the absolute value of the difference between the maximum and the baseline values.

2.8 Statistical Analysis

For the connected speech task, a series of t tests were conducted on the experimental measures from individual participants to determine whether productions with breath group cueing differed from those without breath group cueing. The average values for individual participants were combined and further submitted to a series of paired t tests to determine the effect of breath group cueing for the control and CP groups separately.

For the non-speech task, a series of two-way analyses of variance (ANOVAs) were performed on experimental measures to determine whether there was an effect of place of articulation (i.e., /p/, /t/, /k/), position, or place by position interaction for individual participants. For measures of maximum jaw displacement, the position factor had three levels (i.e., 1 syllable, 3 syllables, and 5 syllables). For all other measures, the position factor had five levels (i.e., 1 syllable, first syllable in a 3-syllable repetition sequence, last syllable in a 3-syllable repetition sequence, first syllable in a 5-syllable repetition sequence, and last syllable in a 5-syllable repetition sequence). The averaged data from individual participants were combined and further submitted to a series of two-way Repeated Measures (RM) ANOVAs to determine the effect of place of articulation and position in the control and CP groups separately. All statistical analyses were performed using SigmaStat 3.5 (Systat Software, Inc., USA). The significance level was set at 0.05. All significant effect was followed up by post-hoc pairwise comparison procedures and plotted into various vertical bar graphs using SigmaPlot 10 (Systat Software, Inc., USA).

2.9 Reliability

To assess measure-remeasurement reliability, 10% of the total tokens of acoustic signals were reanalyzed using the same measurement procedure as used in the first measurement. Results from a series of Pearson Product Moment correlation procedures performed on the corresponding experimental measures revealed relatively high measurement reliability for measures of vowel duration ($r = 0.971$), %jitter ($r = 0.925$), %shimmer ($r = 0.887$), F2 ($r = 0.866$), SNR ($r = 0.855$), VOT ($r = 0.852$), F1 ($r = 0.697$), and F0 ($r = 0.676$).

Chapter 3. Results

This chapter presents separate statistical results from analysis of the connected speech and non-speech data. For the connected speech task, results from a series of t tests and paired t tests, performed on the individual and group data respectively, were shown in Appendices 2 to 15 and Tables 2 to 5 respectively. For the non-connected speech task, results from a series of two-way ANOVAs and two-way RM ANOVAs performed on the individual data and group data were shown in Appendices 16 to 27 and Tables 6 to 9 respectively.

3.1 Connected Speech Task

For the connected speech task, “breath group cueing” was found to have an effect on vowel duration, formant frequencies, %jitter, %shimmer, and SNR. In general, productions with “breath group cueing” were found to be associated with an increase in vowel space areas and phonatory stability.

3.1.1 Vowel Duration

For the control group, vowels produced during the connected speech task were found to exhibit significantly longer durations with breath group cueing (see Tables 2 to 5 and Figure 3). For the CP group, analysis of the group data failed to reveal a significant effect of breath group cueing on vowel durations (see Tables 2 to 5 and Figure 3). However, results from analysis of the individual data revealed that some CP subjects also showed significantly shorter vowel durations when speaking with breath group cueing (see Appendix 3).

3.1.2 Formant Frequencies and Vowel Working Space

For the control group, high vowels, /i/ and /u/, produced during the connected speech task, were found to exhibit significantly lower F1 with breath group cueing (see Tables 2 and 4 and Figure 4). For the CP group, analysis of the group data failed to reveal a significant effect of breath group cueing on F1 or F2 (see Table 3 and Figure 4). However, results from analysis of the individual data revealed that some CP subjects showed a significantly higher F1 when speaking with breath group cueing (see Appendix 5). As shown in Figures 5 and 6, vowel spaces for vowels /i/, /a/, and /u/, produced during the connected speech task, were found to expand with breath group cueing for all CP individuals and the male and female groups. As shown in Figure 7, the tendency for the vowel space area to increase, in productions with breath group cueing, was also found when the vowel space area was calculated based on /i/, /a/, and /ɔ/ except for two participants with CP, one male and one female (CPM2 and CPF1).

3.1.3 Fundamental Frequency

For the control group, the low back vowel /a/, produced during the connected speech task, showed, in average, significantly lower F0 with breath group cueing (see Table 3 and Figure 8). For the connected speech, no significant breath group cueing effect on F0 was found for other vowels in the control group or across all vowels in the CP group (see Tables 2 to 5). However, results from analysis of the individual data revealed that some CP subjects showed significantly higher F0 when speaking with breath group cueing (see Appendix 9 and Figure 8).

3.1.4 Phonatory Stability

For the vowel /a/, produced during the connected speech task, breath group cueing was found to result in significantly lower %jitter and %shimmer for the control group (see Table 3 and Figure 9). For the vowel /ɔ/, produced during the connected speech task, the control group showed significantly lower %shimmer and higher SNR while the CP group lower %jitter and %shimmer and higher SNR when using breath group cueing (see Table 5 and Figure 9).

3.2 Non-Speech Task

As mentioned previously, statistical analyses of data from the non-speech task included two independent variables: "position" and "place of articulation." Position effect refers to changes due to the different positioning of the target production relative to a breath group. For measures of maximum jaw displacement (jaw opening), "position" refers to the length of a breath group, including three levels: (i) monosyllable length, (ii) 3-syllable length, and (iii) 5-syllable length. For all other experimental measures, there were five levels for the factor "position": (i) the syllable in a monosyllabic utterance (P1), (ii) the first syllable in a 3-syllable train (P3-1), (iii) the last syllable in a 3-syllable train (P3-last), (iv) the first syllable in a 5-syllable train (P5-1), and (v) the last syllable in a 5-syllable train (P5-last). The effect of consonant (or place of articulation) refers to changes across the three consonants, namely /p/, /t/, and /k/. The effect of the interaction between the two main factors was referred to as "position-by-place of articulation" interaction effect. For each individual, results from a series of two-way ANOVAs used to determine whether the experimental measures varied by "position" as well as consonant (or place of articulation) were listed in Appendices 16 to 27. The average data obtained from each individual were further combined and submitted to a series of two-way RM ANOVAs to allow for general observation of these effects in the control and CP groups separately (see Tables 6 to 9). Results of a Mann-Whitney U test conducted on the average data combined to determine whether the control and CP groups were different on the experimental measures, were also reported. In general, for the non-speech task, all experimental measures except for

F1 and F2 were found to be affected by the positioning of the target production in a breath group.

3.2.1 Voice Onset Time and Vowel Duration

Results of Mann-Whitney U tests on all average data combined revealed that the CP group (median VOT = 72 ms, median vowel duration = 344 ms) exhibited significantly longer VOT ($T = 174459$, $p < 0.001$) and vowel duration ($T = 232194$, $p < 0.001$) than the control group (median VOT = 66 ms, median vowel duration = 250 ms). In general, for both control and CP groups, measures of VOT were found to vary by place of articulation and position (see Tables 6 to 9). Measures of vowel duration did not show any significant place of articulation effect for either group but showed a significant position effect in the control group for vowels /a/ and /u/ (see Tables 7 and 8). Specific findings are presented in the following section.

3.2.1.1 Place of Articulation Effect

Results from the two-way RM ANOVAs performed on the VOT measures revealed a significant place of articulation effect in both control and CP groups for vowels /i/ and /a/ (see Tables 6 and 7) and only in the control group for vowel /u/ (see Table 8). For both control and CP groups, VOT tended to be shorter in the /p/ context than in the /t/ and /k/ contexts, suggesting that consonants with tongue involvement may delay the onset of voicing for the following vowel (see Figure 10).

3.2.1.2 Position Effect

Results of two-way RM ANOVAs performed on VOT revealed a significant position effect in both control and CP groups for the vowel /a/ (see Table 7) but only in the CP group for the vowel /u/ (see Table 8). As shown in Figure 11, post-hoc tests using the Holm-Sidak method revealed that VOT tended to be longer in the monosyllabic utterances (i.e., p1) than in the multisyllabic utterances, especially in the final syllable of a multisyllabic train (i.e., p3-last, p5-last).

Results of two-way RM ANOVAs performed on vowel duration revealed a significant position effect in the control group for vowels /a/ and /u/ (see Tables 7 and 8) and a significant position-by-place of articulation interaction effect in the control group for vowel /a/ (see Table 7). As shown in Figure 12, vowel durations tended to be shorter in the first syllable of multisyllabic utterances than in the last syllable of multisyllabic utterances or in the monosyllabic utterances. However, for vowel /a/, no significant changes across positions were found in the /t/ context (see Figure 12a).

3.2.2 Formant Frequencies and Vowel Space

Measures for F1 and F2 were found to vary significantly by the consonant context (i.e., place of articulation) but not by position.

3.2.2.1 Place of Articulation Effect

Results from the two-way RM ANOVAs performed on F1 measures revealed a significant place of articulation effect for the CP group in the vowel /i/ context (see Table 6). As shown in Figure 13, post-hoc tests using the Holm-Sidak method revealed that F1 was significantly higher in the /p/ context than in the /t/ and /k/ contexts, suggesting a lower tongue placement in the /p/ context.

Results from the two-way RM ANOVAs performed on F2 measures revealed a significant place of articulation effect in the control group for the vowel /u/ and in the CP group for vowels /i/ and /a/ (see Tables 6 to 9). As shown in Figure 14, F2 tended to be lower in the /p/ context than in the /t/ and /k/ contexts, suggesting a more backward tongue placement in the /p/ context.

3.2.2.2 Position Effect

Results from the two-way RM ANOVAs performed on F2 measures revealed a significant position effect only in the control group for vowels /u/ and /ɔ/ (see Tables 8 and 9). However, post-hoc tests failed to reveal any significant differences between positions.

3.2.2.3 Vowel Space

Figure 15 shows the mean vowel formant frequencies across all positions (i.e. P1, P3-1, P3-last, P5-1 and P5-last) for the non-speech productions by three male subjects with CP (CPM1, CPM2, CPM3) and the male control group, including eight male controls (NM5, NM6, NM7, NM10, NM12, NM13, NM15, NM16). Figure 16 shows the mean vowel formant frequencies across all positions for the non-speech productions by the female subject with CP (CPF1) and the female control group, including eight female controls (NF1, NF2, NF3, NF4, NF8, NF9, NF11 and NF14). Figure 17 displays the size of the vowel working space (in Hz^2) across all positions for the non-speech productions by the four CP subjects (CPM1, CPM2, CPM3, CPF4) and the male and female control groups based on the /i/, /a/, and /u/ (Figure 17a) and /i/, /a/, and /ɔ/ (Figure 17b) separately.

Visual analysis of Figure 17 revealed that the final syllable in a multisyllabic utterance tended to be associated with a smaller /i, a, u/ vowel space in the male control group but a larger vowel space in the female control group as compared with the initial syllable in the utterance. In contrast, CP males tended to show a larger vowel space in the final syllable in a multisyllabic utterance than in the initial syllable (Figure 17). Based on /i/, /a/, and /u/, the one CP female also showed a smaller vowel space for productions in the final syllable position of the 5-syllable production (Figure 17a).

3.2.3 Fundamental Frequency

Fundamental frequency was found to vary by position for the control group but not by place of articulation for either the control or CP group. As shown in Tables 6 to 9, results from the two-way RM ANOVAs performed on F0 measures revealed a significant position effect only in the control group for vowels /a/, /u/, and /ɔ/ (see Tables 7 to 9). As shown in Figure 18, production of the final syllable in a multisyllabic utterance tended to be associated with a lower F0 than that of the initial syllable of the multisyllabic utterance or monosyllabic productions.

3.2.4 Phonatory Stability

Measures of phonatory stability, including %jitter, %shimmer, and SNR, were found to vary by position but not by place of articulation except for the SNR measure from the vowel /a/ in the control group.

3.2.4.1 Place of Articulation Effect

Results of two-way RM ANOVAs performed on the SNR measures revealed a significant place of articulation effect for the control group with the vowel /a/ (see Table 7). As shown in Figure 19, for the control group with the vowel /a/, SNR was significantly higher in the /p/ context than in the /t/ and /k/ contexts.

3.2.4.2 Position Effect

For %jitter measures, results of two-way RM ANOVAs revealed a significant position effect in the control group with vowels /i/, /a/, and /u/ (see Tables 6 to 8) and in the CP group with the vowel /ɔ/ (see Table 9). For %shimmer measures, results of two-way RM ANOVAs revealed a significant position effect only in the control group with vowels /i/, /a/, and /u/ (see Tables 6 to 8). As shown in Figures 20 and 21, the initial syllable in a multisyllabic utterance tended to be associated with lower %jitter and %shimmer than the other positions. For SNR measures, results of two-way RM ANOVAs revealed a significant position effect for all vowels in both control and CP groups (see Tables 6 to 9). As shown in Figure 22, the initial syllable in a multisyllabic utterance tended to be associated with a higher SNR than the other positions.

3.2.5 Speed Quotient and Open Quotient

Results from two-way RM ANOVAs performed on the SQ and OQ measures obtained from the CP group only revealed a significant place of articulation effect on SQ for vowel /ɔ/ (see Table 9). However, post-hoc tests using the Holm-Sidak method failed to reveal any significant pairwise comparisons.

Results from two-way RM ANOVAs performed on the SQ and OQ measures obtained from the control group revealed a significant position-by-place of articulation interaction effect on both measures for the vowel /ɔ/. Post-hoc tests using the Holm-Sidak method revealed that monosyllabic utterances were associated with lower OQ and higher SQ than in multisyllabic utterances in the /k/ context (see Figures 23 and 24). In addition, the initial syllable (i.e. P3-1) in a multisyllabic utterance tended to be associated with higher SQ and lower OQ values than the final syllable (P5-last) in multisyllabic utterances in the /t/ context (see Figures 23 and 24).

3.2.6 Maximum Jaw Displacement

Results of Mann-Whitney U tests on all data combined revealed that the CP group (median jaw opening = 9.6 mm) exhibited significantly larger jaw opening

($T = 61672$, $p < 0.001$) than the control group (median jaw opening = 8.3 mm). Maximum jaw displacement was generally found to vary by place of articulation for the control group but not for the CP group regardless of vowel context. The position effect on maximum jaw displacement was only significant for the CP group and only in the vowel /i/ context.

3.2.6.1 Place of Articulation Effect

Results of two-way RM ANOVAs performed on measures of maximum jaw displacement averaged across all trials revealed, for each of the four vowels, a significant place of articulation effect for the control group but not for the CP group (see Tables 6 to 9). Post-hoc pairwise tests using the Holm-Sidak method revealed that the alveolar plosive (i.e., /t/) was associated with a significantly smaller jaw displacement than the bilabial (i.e., /p/) and velar (i.e., /k/) plosives. However, in the vowel /i/ context, this consonant was significant only for the 3-syllable and 5-syllable productions (see Figure 25).

3.2.6.2 Position Effect

Based on results from the averaged group data, the effect of the length of breath group (or position) was only significant in the CP group and only for the vowel /i/ (see Table 6). As shown in Figure 26, the single syllable production was associated with a significantly smaller jaw opening than both 3-syllable and 5-syllable productions.

3.3 Summary of Main Findings

The main findings of this study are:

1. **Effect of Breath Group Cueing:** Breath group cueing was found to lead to the expansion of vowel space (due to lower F1 for high vowels /i/ and /u/) and improved phonatory stability (lower %jitter and %shimmer and higher SNR) in connected speech for both control and CP groups.
2. **Position Effect:** The length of a breath group was found to affect all experimental measures. Productions in the final syllable of a multisyllabic train were associated with a decrease in phonatory stability and vowel space area.
3. **Place of Articulation Effect:** Place of articulation was found to affect measures of VOT, F1, F2, SNR, and maximum jaw displacement.

4. **Group Difference:** The CP group was generally found to exhibit longer VOT, longer vowel duration, higher F2, smaller vowel space, and larger extent of jaw opening than the control group.

Chapter 4. Discussion

This chapter provides a discussion of the findings in relation to the research question, previous research, clinical implications, and limitation of the study and future studies. Findings from the present study revealed that breath group control as a facilitative strategy was effective in expanding the vowel working space for all CP subjects in the connected speech task. However, breath group control resulted in minimal changes of vowel space in the speech production of control subjects. This is likely to be related to a ceiling effect as previously hypothesized. Place of articulation of the consonant preceding the targeted vowels had minimal impact on the effect of breath group control on formant frequencies. In addition, the extent of jaw displacement was greater in multisyllabic utterances than in monosyllabic ones. Over the course of a breath group, phonatory stability tended to deteriorate toward the end of a breath group in multisyllabic utterances as predicted. These findings provided evidences showing that breath group control would be useful for enhancing articulatory and phonatory stability. Specific findings for the experimental measures in this study are discussed in the following section.

4.1 Voice Onset Time and Vowel Duration

In both CP and control groups, VOT was found to be the longest in monosyllabic utterances (P1) and the shortest in the final syllable of multisyllabic utterances (P3-last and P5-last). This finding supported the theory proposed by Hoit et al. (1993) that VOT was partly contingent upon an individual's lung volume, with reduced lung volume being associated with reduced VOT. As air tends to run out toward the end of a breath group and thus the final syllable is most likely to be produced with reduced lung volume, the finding of a decrease of VOT in the final syllable of a multisyllabic utterance supports the positive relationship between lung volume and VOT. Furthermore, consonant context was also found to be a contributing factor to VOT in the current study. The finding that VOT for the nonsense speech-like utterances beginning with /p/ was significantly shorter than utterances beginning with /t/ and /k/ was consistent with the results reported by Klatt (1975) and Port and Rotunno (1979) that the average VOT for /p/ (Klatt: 47 ms, Port and Rotunno: 64 ms) was generally shorter than that of /t/ (Klatt: 65 ms, Port and Rotunno: 73 ms) and /k/ (Klatt: 70 ms, Port and Rotunno: 90 ms) in neurologically healthy adults. This finding is most likely due to the difference in the complexity of the relationship between the articulators involved, as the production of bilabial voiceless plosive /p/ requires the coordination of the lip and laryngeal movements, a mechanism relatively simpler than that in the production of alveolar (/t/) or velar (/k/) voiceless plosives, which involves tongue movement that may affect the laryngeal positioning for vocal fold movements due to the attachments of the tongue and the larynx to the hyoid bone.

Vowels produced by CP subjects were found in this study to be longer in duration than those produced by control subjects. Since the duration of corner vowels has been considered an objective measure for assessing the stability of articulation, the ability to sustain and control respiration, and the ability to coordinate respiratory, laryngeal, and supralaryngeal activity (Jayaram, 1997), vowel prolongation might be indicative of a speaking difficulty. Indeed, increased vowel duration has been considered one of the characteristics of dysarthric speech (Turner et al., 1995). The present finding that the CP group tended to exhibit longer vowel duration than the control group suggested that speakers with CP had more difficulty maintaining the stability of articulation. The finding in the control group that vowel duration tended to be longer in the final syllable of a multisyllabic utterance than in the initial syllable supported the hypothesis that subjects would have more difficulty maintaining sufficient air to sustain vowel articulation towards the end of a longer multisyllabic utterance. The lack of a position effect on vowel duration in the CP group may be related to the greater inconsistency or between-trial variation shown in the CP speech. In addition, results from the connected speech showed longer vowel duration with breath group cueing for the control group only, suggesting that the effect of speech phrasing on segmental timing might differ between control speakers and individuals with CP.

4.2 Formant Frequencies and Vowel Working Space

Formant frequencies, as previously mentioned, are related to tongue positioning and vocal tract constriction, with a higher F1 reflecting a lower tongue positioning or a higher degree of pharyngeal constriction and a higher F2 a more forward tongue positioning or a less degree of posterior oral constriction (Baken, 1987). Although no position effect was found in this study for formant frequencies, the vowel working space was found to vary by position. For the non-speech task, the effect of position on vowel space area was inconsistent between the two experimental groups. For the connected speech task, all CP subjects demonstrated an expansion of vowel working spaces with breath control cueing. During the habitual condition (i.e., without breath group cueing), vowel working spaces were narrower and more restricted, particularly with subject CPM3, who was diagnosed with CP of the spastic monoplegic type. A compressed vowel space has been considered to be related to the restriction of tongue typical of individuals with CP (Liu, et al., 2005), other speakers with dysarthria (Liss, Spitzer, Caviness, Adler & Edwards, 2000; Turner, et al., 1995; Ziegler & von Cramon, 1983), and the hearing impaired (Monsen, 1976) as well as neurologically healthy speakers (Bradlow, Torretta, & Pisoni, 1996; Krause & Braida, 2004). Evidences have been provided in the literature showing that larger vowel working space areas correspond to clearer (Krause & Braida, 2004), more intelligible speech (Bradlow, Torretta, & Pisoni, 1996; Liu et al., 2005). Therefore, the expansion of vowel space in the CP group with breath group cueing demonstrated that breath group control was useful for speech enhancement.

The expansion of vowel working space in response to breath group control in the control groups, particularly with males, was minimal. However, the finding from the control group is consistent with the observation in the previous studies that the vowel space in males is more reduced than that in females (Bradlow, Torretta, & Pisoni, 1996; Turner et al., 1995).

It has been reported that vowel working space may be affected by the rate of speech. For example, Fourakis (1991) and Turner et al. (1995) reported in their studies that reduced rate of speech was associated with vowel space expansion in neurologically healthy adults. Tsao et al. (2006), in a study of vowel space as a function of vocal rate in 30 neurological healthy adults, including 15 (8 males and 7 females) “fast” speakers, and 15 (7 males and 8 females) “slow” speakers, found that the mean size of vowel space did not differ significantly between the two groups. However, the size of vowel space obtained from the slow speakers was significantly more variable than those obtained from the fast speakers. This variability was also shown in the study in the difference between the control and CP groups on the change of vowel duration. The present finding for the measure of vowel duration in the connected speech task showed that productions with breath group cueing tended to be associated with longer vowel duration in the control group but not in the CP group. The association between vowel duration and vowel space was not evident. Therefore, although the breath group cues provided in the present study may have the potential to reduce the subject’s rate of speech, the rate of speech was not systematically controlled across or within speakers to allow for an investigation of the effect of speech rate on vowel space.

Changes in vowel space have also been studied in relation to lung volume in neurologically healthy speakers. In a study of eight adult females, Watson et al. (2003)

investigated the effect of lung initiation levels on the corner vowel working space. The average vowel working spaces were calculated for the vowels produced at low (40% of vital capacity), habitual (60% vital capacity), and high (80% vital capacity) lung initiation level in connected text. Results revealed that the vowel working space obtained from speech produced at habitual lung volume was the largest, followed in order by that at high lung volume and low lung volume but that the only significant difference in the size of vowel space was between habitual and low lung volume conditions. The authors proposed that the reduced vowel working space was not likely to be associated with rate or loudness as no change was reported for rate across the different lung volumes, and increased loudness at high lung volume did not result in significant vowel space difference. The authors attributed the reduced vowel space in association with low lung volume to a "gaining down" phenomenon, where the reduction in expiratory muscular effort impinged on the articulatory mechanism, resulting in the shrinkage of the vocal tract as represented by the vowel working space. It was uncertain, however, as to why the vowel space area remained relatively unchanged from habitual lung volume to higher lung volume.

In the present study, the vowel working spaces expanded for all CP subjects when the breath group control strategy was in place. This may be related to a change in lung volume similar to those reported from the study by Watson at al. (2003). Since vital capacity have been reported to be reduced in individuals with CP, the habitual lung volume may be described as being similar to the low lung volume of neurologically healthy speakers from Watson et al.'s (2003) study. Assuming lung volume increased when breath group control strategy was in place, the increased lung volume in the CP subjects with breath group control may reach a level similar to the habitual lung volume of the neurologically healthy speakers from Watson et al.'s (2003) study.

In summary, it appears that breath group control was effective in releasing the restriction of the tongue, and may be associated with increase speech intelligibility and lung volume, especially for individuals with spastic CP.

4.3 Phonatory Stability

Percent jitter, %shimmer and SNR were included in the present investigation to assess the effect of breath control cues on phonatory stability, which was often found to be aversely affected in dysarthric speech (Duffy, 1995). An increase in %jitter or %shimmer or a decrease in SNR is an indication of increased phonatory instability (Gelfer, 1995). In the present study, %jitter and %shimmer values were generally higher for the CP group than the control group. Individuals with pathological voice disorders secondary to disorders such as ALS (Lundy, Roy, Xue, Casiano & Jassir, 2004; Zhang & Jiang, 2008) and Parkinson's disease (Zhang & Jiang, 2008) have been reported to have higher jitter and shimmer values as compared with neurologically healthy individuals. In a comparison of adults with pathological voice disorder secondary to a variety of disorders (including Parkinson's Disease, polypoid degeneration, and presbyphonia) and neurologically healthy adults, Zhang and Jiang (2008) reported both jitter and shimmer obtained from a vowel /a/ sustaining task were significantly higher for the 10 men and 13 women with pathological voice disorders than the 15 men and 8 women in the control group. In a study of 29 young adult women, Gelfer (1995) examined the effects of vowel type, vocal intensity, and F0 on %jitter, %shimmer, and SNR and reported that %jitter tended to be higher for the low back vowel /a/ than the high front vowel /i/. Findings for the female control group in the present study were in agreement with Gelfer's observation. The finding of a vowel difference in %jitter measures may be related to the higher intrinsic pitch associated with a high vowel, a well observed phenomenon that could be explained based on the physical linkage hypothesis that the larynx height was affected by the tongue movements needed for vowel formation (Lin et al., 2000).

In addition to vowel effect, measures of %jitter for the vowel /i/, /a/ and /u/ in the control group and the vowel /ɔ/ in CP group were found in this study to be significantly affected by position. Percent shimmer was also significantly affected by position in the control group across all vowels included in this study. Specifically, it was found that measures of %jitter and %shimmer in both the CP group and the control group were lowest in the initial syllable (P3-1, P5-1) and highest in the final syllable (p3-Last, P5-Last) in a multisyllabic utterance irrespective of the vowel context. This finding indicated that the stability of VF vibrations tended to deteriorate towards the end of a long breath group. In addition, both %jitter and %shimmer in a monosyllabic utterance were generally lower than those obtained from the initial syllable of a multisyllabic utterance. For both control and CP groups, position had the greatest effect on the SNR measures, with the initial syllable in a multisyllabic utterance showing the highest SNR than in any the other positions irrespective of the vowel contexts. These findings may be related to physiological changes found in voicing associated with decreased intensity as reported by Orlikoff and Kahane (1991). It is most likely that speakers would increase the effort to inhale before production of a long multisyllabic utterance to ensure there is a sufficient amount of air for the utterance in one breath. The increased inhalation effort may lead to a higher intensity for the production of the initial syllable and thus greater phonatory stability, which is reflective of greater efficiency of transferring the subglottal pressure to the acoustic power due to the airflow-based buildup of subglottal pressure. Towards the end of the utterance, however, the airflow is reduced, which may cause the laryngeal muscles to stiffen to increase subglottal pressure. Excessive glottal resistance or laryngeal stiffness has been considered an inefficient way to increase acoustic power. At low lung volume, the subglottal air pressure may be reduced to the point where vocal folds are more susceptible to factors causing phonatory instability. The present finding that the perturbation measures obtained from CP subjects showed a similar trend as that found in the control subjects confirms that %jitter, %shimmer, and SNR are sensitive and objective measures of phonatory stability as proposed by previous research.

4.4 Speed Quotient and Open Quotient

The two temporal measures derived from EGG signals, SQ and OQ, were included in this study as direct measures of the laryngeal behaviors. As mentioned previously, speed quotient is the ratio of opening time, defined as the time it takes for vocal fold contact to change from a predetermined level of maximum (90% in this study) to the minimum (10%), to closing time, defined as the time it takes for vocal contact to change from the minimum back to the maximum. Speed quotient reflects glottal efficiency because the closing time is relatively constant with mainly the passive recoil of the vocal folds involved and, therefore, an excessively short or long opening time leading to an abnormally high or low SQ value would indicate glottal inefficiency. Likewise, OQ, defines as the ratio of the duration of the open phase of vocal folds to the total duration of the glottal cycle, would indicate whether vocal folds are sufficiently adducted. Although subjects included in this study were not characterized by pathological voice, it was hypothesized that changes in SQ and OQ might reflect the impact of breath control on the vibratory patterns of vocal folds. Control subjects from the current study demonstrated that the length of a breath group and the place of articulation of the consonant preceding the vowel indeed significantly affected SQ and OQ. For example, in the contexts of the velar plosive /k/ and the vowel /ɔ/, SQ in monosyllabic utterances was shown to be significantly higher than those in multisyllabic utterances were. This finding suggests that the elevation of the back of the tongue required for the production of velar plosive /k/ combined with the downward and forward movement in the production of the vowel /ɔ/

may create a vocal tract configuration that imparts restriction on the vocal folds. When air is diminished toward the end of a multisyllabic utterance, the vocal folds may not oscillate efficiently and thus may exert greater glottal resistance to build up pressure.

4.5 Jaw Displacement

The finding in the vowel /i/ context from the CP group that a longer breath group tended to be associated with a larger extent of jaw opening may be reflective of a poor postural control for maintaining a stable jaw opening over the course of a long breath group. The finding that this position difference was most evident in the vowel /i/ suggested that production requiring tongue elevation might be harder to stabilize.

The alveolar plosive /t/ was shown in the control group to be associated with a smaller jaw displacement than bilabial and velar plosives. This finding suggested that the forward tongue placement required for the production of the alveolar sound /t/ posed a movement restriction on the tongue. As a larger degree of jaw displacement requires the lowering of the mandible, which requires contraction of two muscles that insert into the tongue (i.e., geniohyoid and anterior belly of digastric), the pulling for tongue forwardness may inevitably result in a compromise in jaw opening. The finding that the place of articulation effect on jaw displacement was most evident in utterances with a longer breath group suggests that the difference in the tongue movement restrictions posed by different places of articulation may increase as the amount of airflow decreased toward the end of a breath group leading to further deterioration of the oral-laryngeal coordination.

4.6 Clinical Implication

Prelimenary findings from the current study offer some clinical implications for speakers with dysarthria secondary to CP. The current study confirms that tongue momevments in CP speakers are more restricted than nuerologically healthy control speakers. Such restriction can be objectively reflected by the vowel space, as shown in previous study and the present findings. Althought results varied across dysarhtric speakers with differnt types of CP and different levels of severity, findings from this study suggested that breath group cues were conductive to vowel space expansion, which has been shown in the literature to be assoicated with greater speech intelligibility.

Findings on perturbation measures in this study revealed that phonatory stability deteriorated towards the end of a multisyllabic utterance as the number of syllable in a breath group increased. These finding not only provided instrumental evidences showing a positive effect of breath group control as a facilitative strategy for individuals with CP but also demonstrated the usefulness of the proposed instrumental measures in monitoring the speech and voice of the CP population. As speech-language therapists often rely solely on perceptual findings to evalaute and monitor progress of dysarthric speech in clinical settings, the results of the present study show that acoustic measures, particularly F1 and F2, can provide objective data to complement perceptual findings in a non-invasive and consistent manner.

4.7 Limitations of the Study and Future Directions

There are a number of limitations to the generalization of the present findings. Firstly, the number of CP subjects included in this study was small and thus the observations made in this study may not be representative of the clinical population. Studies consist of a larger sample size is needed for follow-up studies. Future studies may include more CP subjects in each type and at different levels of severity to allow for a comparison of the breath control effect on different subject type and thus identify patients most responsive to this type of treatment. Secondly, the present study included acoustic, EGG, and facial tracking measures but no perceptual measures. While modification of breath group length has been reported to enhance naturalness of dysarthric speech

(Bellaire et al., 1986) and speech intelligibility has been shown to be positively related to the expansion of vowel working space (e.g. Krause & Braida, 2004; Liu et al., 2005), perceptual analysis of the speech signals collected from the present study would have been useful for identifying and verifying the relationship between speech intelligibility, speech naturalness, and the acoustical, EGG, and facial tracking measures. Lastly, the subject's tasks involved syllable repetition and passage reading tasks in one session. Future studies involving spontaneous speech and/or multiple sessions are necessary to investigate the long-term effect of speech phrasing/pacing.

4.8 Conclusion

In conclusion, the vibratory frequency, periodicity, and pattern of the vocal folds were found to worsen over the course of a breath group for both CP and control groups. The finding that breath group cueing led to an increase in vowel space area and phonatory stability supported the use of speech phrasing (i.e., breath group control) as a facilitative strategy to enhance the speech and voice of dysarthric speakers with CP. The expansion of vowel space due to breath group control was more robust in the connected speech reading, especially for the CP subjects.

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TABLE 1. Subject information for CP subjects

Participant	Age	Gender	Years since onset	Type of cerebral palsy	Type of dysarthria
CP 1	42	M	41	Spastic Quadraplegic	Spastic
CP 2	40	M	38	Athetoid	Athetoid
CP 3	36	M	36	Spastic Monoplegic	Spastic
CP 4	19	F	19	Ataxia	Ataxic

TABLE 2. Results of paired t-tests on the “breath group cueing” effect for the connected speech data from the control and CP groups on all experimental measures for the vowel /i/.

	N	t	df	p
Control				
Vowel Duration	15	-2.680	14	0.018*
F1	15	2.442	14	0.028*
F2	15	-0.0209	14	0.984
F0	15	1.298	14	0.215
%jitter	15	1.419	14	0.178
%shimmer	15	-0.0381	14	0.970
SNR	15	-0.977	14	0.345
CP				
Vowel Duration	4	0.685	3	0.543
F1	4	-2.106	3	0.126
F2	4	-1.208	3	0.314
F0	4	-1.697	3	0.188
%jitter	4	0.305	3	0.780
%shimmer	4	1.467	3	0.239
SNR	4	-1.271	3	0.293

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 3. Results of paired t-tests on the "breath group cueing" effect for the connected speech data from the control and CP groups on all experimental measures for the vowel /a/.

	N	t	df	p
Control				
Vowel Duration	15	-6.305	14	<0.001**
F1	15	-0.591	14	0.564
F2	15	1.847	14	0.086
F0	15	3.078	14	0.008*
%jitter	15	2.526	14	0.024*
%shimmer	15	3.440	14	0.004**
SNR	15	-1.845	14	0.086
CP				
Vowel Duration	4	0.466	3	0.673
F1	4	-1.345	3	0.271
F2	4	0.422	3	0.702
F0	4	-0.966	3	0.405
%jitter	4	-0.213	3	0.845
%shimmer	4	-0.280	3	0.797
SNR	4	-1.959	3	0.145

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 4. Results of paired t-tests on the "breath group cueing" effect for the connected speech data from the control and CP groups on all experimental measures for the vowel /u/.

	N	t	df	p
Control				
Vowel Duration	15	-6.209	14	<0.001**
F1	15	2.179	14	0.047*
F2	15	0.665	14	0.517
F0	15	0.782	14	0.447
%jitter	15	-0.852	14	0.408
%shimmer	15	-2.096	14	0.055
SNR	15	0.256	14	0.802
CP				
Vowel Duration	4	0.362	3	0.742
F1	4	-1.307	3	0.282
F2	4	1.051	3	0.370
F0	4	-1.935	3	0.148
%jitter	4	0.928	3	0.422
%shimmer	4	1.421	3	0.250
SNR	4	-0.871	3	0.448

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 5. Results of paired t-tests on the “breath group cueing” effect for the connected speech data from the control and CP groups on all experimental measures for the vowel /ɔ/.

		t	df	
Control				
Vowel Duration	15	-8.763	14	<0.001**
F1	15	0.834	14	0.418
F2	15	0.463	14	0.651
F0	15	0.0119	14	0.991
%jitter	15	-0.136	14	0.894
%shimmer	15	2.141	14	0.050*
SNR	15	-3.458	14	0.004**
CP				
Vowel Duration	4	0.319	3	0.770
F1	4	-1.241	3	0.303
F2	4	0.575	3	0.606
F0	4	-0.921	3	0.425
%jitter	4	8.018	3	0.004**
%shimmer	4	5.725	3	0.011*
SNR	4	-3.727	3	0.034*

*Significant at 0.05 level
**Significant at 0.005 level

*Significant at 0.05 level

TABLE 6. Results of two-way RM ANOVAs for the non-speech data from the control and CP groups on all experimental measures with the vowel /i/.

	N	Place of Articulation	Position	Place of Articulation by Position Interaction
Control				
Jaw opening	144	F (2, 30) = 10.086, p < 0.001**	F (2, 30) = 3.1900, p = 0.055	F (4, 60) = 4.8530, p = 0.002**
VOT	240	F (2, 120) = 10.33, p < 0.001**	F (4, 120) = 1.062, p = 0.383	F (8, 120) = 1.042, p = 0.408
Vowel Duration	240	F (2, 120) = 0.872, p = 0.428	F (4, 120) = 0.733, p = 0.573	F (8, 120) = 0.968, p = 0.464
F1	240	F (2, 120) = 0.278, p = 0.759	F (4, 120) = 1.889, p = 0.124	F (8, 120) = 0.456, p = 0.885
F2	240	F (2, 120) = 1.192, p = 0.318	F (4, 120) = 1.064, p = 0.382	F (8, 120) = 0.937, p = 0.488
F0	240	F (2, 120) = 1.024, p = 0.371	F (4, 120) = 0.764, p = 0.553	F (8, 120) = 10.98, p = 0.445
%jitter	240	F (2, 120) = 0.104, p = 0.902	F (4, 120) = 4.137, p = 0.005**	F (8, 120) = 1.712, p = 0.102
%shimmer	240	F (2, 120) = 1.408, p = 0.260	F (4, 120) = 4.351, p = 0.004**	F (8, 120) = 1.415, p = 0.197
SNR	240	F (2, 120) = 1.387, p = 0.265	F (4, 120) = 6.470, p < 0.001**	F (8, 120) = 0.967, p = 0.465
Speed Quotient	60	F (2, 24) = 0.952, p = 0.437	F (4, 24) = 0.914, p = 0.487	F (8, 24) = 1.071, p = 0.415
Open Quotient	60	F (2, 24) = 0.820, p = 0.484	F (4, 24) = 0.800, p = 0.548	F (8, 24) = 1.372, p = 0.258
CP				
Jaw Opening	35	F (2, 6) = 0.016, p = 0.984	F (2, 6) = 11.937, p = 0.008*	F (4, 12) = 0.519, p = 0.724
VOT	60	F (2, 24) = 10.8, p = 0.010*	F (4, 24) = 2.789, p = 0.076	F (8, 24) = 0.365, p = 0.929
Vowel Duration	60	F (2, 24) = 0.990, p = 0.425	F (4, 24) = 1.163, p = 0.375	F (8, 24) = 0.687, p = 0.699
F1	60	F (2, 24) = 7.229, p = 0.025*	F (4, 24) = 0.790, p = 0.554	F (8, 24) = 0.979, p = 0.475
F2	60	F (2, 24) = 6.106, p = 0.036*	F (4, 24) = 0.117, p = 0.974	F (8, 24) = 0.287, p = 0.964
F0	60	F (2, 24) = 1.199, p = 0.365	F (4, 24) = 2.323, p = 0.116	F (8, 24) = 0.838, p = 0.579
%jitter	60	F (2, 24) = 0.120, p = 0.889	F (4, 24) = 2.357, p = 0.112	F (8, 24) = 1.614, p = 0.173
%shimmer	60	F (2, 24) = 0.242, p = 0.793	F (4, 24) = 2.704, p = 0.081	F (8, 24) = 1.187, p = 0.347
SNR	60	F (2, 24) = 2.355, p = 0.176	F (4, 24) = 5.555, p = 0.009*	F (8, 24) = 1.099, p = 0.398
Speed Quotient	60	F (2, 24) = 0.478, p = 0.642	F (4, 24) = 0.423, p = 0.789	F (8, 24) = 1.035, p = 0.438
Open Quotient	60	F (2, 24) = 2.482, p = 0.164	F (4, 24) = 0.653, p = 0.636	F (8, 24) = 0.875, p = 0.551

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 7. Results of two-way RM ANOVAs for the non-speech data from the control and CP groups on all experimental measures with the vowel /a/.

	N	Place of Articulation	Position	Place of Articulation by Position Interaction
Control				
Jaw Opening	144	F (2, 30) = 10.413, p < 0.001**	F (2, 30) = 2.4730, p = 0.101	F (4, 60) = 1.4850, p = 0.218
VOT	240	F (2, 120) = 35.33, p < 0.001**	F (4, 120) = 5.170, p < 0.001**	F (8, 120) = 0.753, p = 0.645
Vowel Duration	240	F (2, 120) = 0.207, p = 0.814	F (4, 120) = 4.952, p = 0.002**	F (8, 120) = 2.541, p = 0.014*
F1	240	F (2, 120) = 0.019, p = 0.981	F (4, 120) = 0.508, p = 0.730	F (8, 120) = 1.012, p = 0.431
F2	240	F (2, 120) = 1.933, p = 0.162	F (4, 120) = 2.229, p = 0.076	F (8, 120) = 0.883, p = 0.533
F0	240	F (2, 120) = 0.267, p = 0.767	F (4, 120) = 6.508, p < 0.001**	F (8, 120) = 0.782, p = 0.620
%jitter	240	F (2, 120) = 0.088, p = 0.916	F (4, 120) = 4.134, p = 0.005**	F (8, 120) = 0.939, p = 0.487
%shimmer	240	F (2, 120) = 1.875, p = 0.171	F (4, 120) = 4.657, p = 0.002**	F (8, 120) = 0.984, p = 0.452
SNR	240	F (2, 120) = 4.562, p = 0.019*	F (4, 120) = 6.040, p < 0.001**	F (8, 120) = 1.527, p = 0.155
Speed Quotient	60	F (2, 24) = 1.176, p = 0.371	F (4, 24) = 1.550, p = 0.250	F (8, 24) = 0.821, p = 0.592
Open Quotient	60	F (2, 24) = 1.192, p = 0.367	F (4, 24) = 1.726, p = 0.209	F (8, 24) = 0.913, p = 0.522
CP				
Jaw opening	36	F (2, 6) = 0.3790, p = 0.700	F (2, 6) = 0.1120, p = 0.896	F (4, 12) = 0.781, p = 0.559
VOT	60	F (2, 24) = 6.148, p = 0.035*	F (4, 24) = 4.408, p = 0.020*	F (8, 24) = 0.595, p = 0.772
Vowel Duration	60	F (2, 24) = 0.699, p = 0.533	F (4, 24) = 1.041, p = 0.426	F (8, 24) = 1.109, p = 0.392
F1	60	F (2, 24) = 1.601, p = 0.277	F (4, 24) = 2.019, p = 0.156	F (8, 24) = 1.584, p = 0.182
F2	60	F (2, 24) = 7.046, p = 0.027*	F (4, 24) = 0.257, p = 0.900	F (8, 24) = 2.250, p = 0.060
F0	60	F (2, 24) = 0.872, p = 0.465	F (4, 24) = 0.763, p = 0.569	F (8, 24) = 1.166, p = 0.359
%jitter	60	F (2, 24) = 0.350, p = 0.718	F (4, 24) = 2.534, p = 0.095	F (8, 24) = 0.917, p = 0.520
%shimmer	60	F (2, 24) = 0.221, p = 0.808	F (4, 24) = 2.588, p = 0.091	F (8, 24) = 0.371, p = 0.926
SNR	60	F (2, 24) = 0.383, p = 0.697	F (4, 24) = 9.330, p < 0.001**	F (8, 24) = 0.726, p = 0.668
Speed Quotient	60	F (2, 24) = 2.415, p = 0.170	F (4, 24) = 2.535, p = 0.095	F (8, 24) = 2.139, p = 0.072
Open Quotient	60	F (2, 24) = 2.227, p = 0.189	F (4, 24) = 2.227, p = 0.123	F (8, 24) = 1.857, p = 0.115

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 8. Results of two-way RM ANOVAs for the non-speech data from the control and CP groups on all experimental measures with the vowel /u/.

	N	Place of Articulation	Position	Place of Articulation x Position
Control				
Jaw Opening	144	F (2, 30) = 5.6150, p = 0.008*	F (2, 30) = 1.5550, p = 0.228	F (4, 60) = 0.5660, p = 0.688
VOT	240	F (2, 120) = 20.25, p < 0.001**	F (4, 120) = 0.708, p = 0.589	F (8, 120) = 0.595, p = 0.781
Vowel Duration	240	F (2, 120) = 2.777, p = 0.078	F (4, 120) = 9.396, p < 0.001**	F (8, 120) = 1.312, p = 0.244
F1	240	F (2, 120) = 0.512, p = 0.605	F (4, 120) = 0.851, p = 0.499	F (8, 120) = 1.093, p = 0.373
F2	240	F (2, 120) = 8.928, p < 0.001**	F (4, 120) = 2.652, p = 0.042*	F (8, 120) = 0.428, p = 0.902
F0	240	F (2, 120) = 3.091, p = 0.060	F (4, 120) = 13.52, p < 0.001**	F (8, 120) = 1.735, p = 0.097
%jitter	240	F (2, 120) = 3.102, p = 0.060	F (4, 120) = 5.923, p < 0.001**	F (8, 120) = 0.975, p = 0.459
%shimmer	240	F (2, 120) = 1.464, p = 0.247	F (4, 120) = 4.411, p = 0.003**	F (8, 120) = 0.859, p = 0.553
SNR	240	F (2, 120) = 3.205, p = 0.055	F (4, 120) = 9.366, p < 0.001**	F (8, 120) = 0.802, p = 0.602
Speed Quotient	60	F (2, 24) = 0.340, p = 0.724	F (4, 24) = 0.954, p = 0.467	F (8, 24) = 1.322, p = 0.280
Open Quotient	60	F (2, 24) = 0.155, p = 0.860	F (4, 24) = 1.713, p = 0.212	F (8, 24) = 1.213, p = 0.333
CP				
Jaw Opening	36	F (2, 6) = 0.2230, p = 0.806	F (2, 6) = 1.6840, p = 0.263	F (4, 12) = 1.160, p = 0.376
VOT	60	F (2, 24) = 4.279, p = 0.070	F (4, 24) = 4.538, p = 0.018*	F (8, 24) = 0.314, p = 0.953
Vowel Duration	60	F (2, 24) = 2.321, p = 0.179	F (4, 24) = 0.695, p = 0.610	F (8, 24) = 0.548, p = 0.808
F1	60	F (2, 24) = 2.607, p = 0.153	F (4, 24) = 1.044, p = 0.425	F (8, 24) = 0.745, p = 0.652
F2	60	F (2, 24) = 1.410, p = 0.315	F (4, 24) = 0.470, p = 0.757	F (8, 24) = 0.173, p = 0.993
F0	60	F (2, 24) = 3.584, p = 0.095	F (4, 24) = 0.260, p = 0.898	F (8, 24) = 1.003, p = 0.459
%jitter	60	F (2, 24) = 4.606, p = 0.061	F (4, 24) = 3.245, p = 0.051	F (8, 24) = 0.699, p = 0.689
%shimmer	60	F (2, 24) = 2.050, p = 0.210	F (4, 24) = 2.287, p = 0.120	F (8, 24) = 1.321, p = 0.281
SNR	60	F (2, 24) = 0.601, p = 0.578	F (4, 24) = 4.755, p = 0.016**	F (8, 24) = 0.893, p = 0.537
Speed Quotient	60	F (2, 24) = 1.727, p = 0.256	F (4, 24) = 1.006, p = 0.442	F (8, 24) = 0.484, p = 0.855
Open Quotient	60	F (2, 24) = 2.398, p = 0.172	F (4, 24) = 1.435, p = 0.282	F (8, 24) = 0.244, p = 0.978

*Significant at 0.05 level
**Significant at 0.005 level

TABLE 9. Results of two-way RM ANOVAs for the non-speech data from the control and CP groups on all experimental measures with the vowel /ɔ/.

	N	Place of Articulation	Position	Place of Articulation x Position
Control				
Jaw opening	144	F (2, 30) = 10.342, p < 0.001**	F (2, 30) = 0.5030, p = 0.610	F (4, 60) = 0.3110, p = 0.870
VOT	240	F (2, 120) = 2.772, p = 0.078	F (4, 120) = 0.417, p = 0.417	F (8, 120) = 0.799, p = 0.605
Vowel Duration	240	F (2, 120) = 0.944, p = 0.400	F (4, 120) = 2.376, p = 0.062	F (8, 120) = 2.376, p = 0.367
F1	240	F (2, 120) = 0.653, p = 0.528	F (4, 120) = 1.078, p = 0.375	F (8, 120) = 1.324, p = 0.238
F2	240	F (2, 120) = 1.061, p = 0.359	F (4, 120) = 2.631, p = 0.043*	F (8, 120) = 0.822, p = 0.584
F0	240	F (2, 120) = 2.421, p = 0.106	F (4, 120) = 17.76, p < 0.001**	F (8, 120) = 1.457, p = 0.180
%jitter	240	F (2, 120) = 0.688, p = 0.510	F (4, 120) = 2.151, p = 0.085	F (8, 120) = 0.826, p = 0.581
%shimmer	240	F (2, 120) = 1.534, p = 0.232	F (4, 120) = 1.341, p = 0.265	F (8, 120) = 1.083, p = 0.380
SNR	240	F (2, 120) = 0.244, p = 0.785	F (4, 120) = 3.677, p = 0.010*	F (8, 120) = 0.768, p = 0.631
Speed Quotient	60	F (2, 24) = 0.708, p = 0.530	F (4, 24) = 2.356, p = 0.112	F (8, 24) = 6.762, p <0.001**
Open Quotient	60	F (2, 24) = 0.539, p = 0.609	F (4, 24) = 2.081, p = 0.147	F (8, 24) = 5.882, p <0.001**
CP				
Jaw opening	36	F (2, 6) = 3.5090, p = 0.098	F (2, 6) = 2.9520, p = 0.128	F (4, 12) = 0.571, p = 0.689
VOT	60	F (2, 24) = 4.459, p = 0.065	F (4, 24) = 3.117, p = 0.056	F (8, 24) = 1.163, p = 0.360
Vowel Duration	60	F (2, 24) = 0.082, p = 0.922	F (4, 24) = 2.236, p = 0.126	F (8, 24) = 0.962, p = 0.487
F1	60	F (2, 24) = 0.711, p = 0.528	F (4, 24) = 0.875, p = 0.507	F (8, 24) = 0.967, p = 0.484
F2	60	F (2, 24) = 1.187, p = 0.368	F (4, 24) = 1.398, p = 0.293	F (8, 24) = 1.243, p = 0.318
F0	60	F (2, 24) = 3.584, p = 0.095	F (4, 24) 0.260, p = 0.898	F (8, 24) = 1.003, p = 0.459
%jitter	60	F (2, 24) = 1.568, p = 0.283	F (4, 24) = 5.990, p = 0.007*	F (8, 24) = 1.202, p = 0.339
%shimmer	60	F (2, 24) = 2.372, p = 0.174	F (4, 24) = 3.005, p = 0.062	F (8, 24) = 1.303, p = 0.289
SNR	60	F (2, 24) = 1.852, p = 0.236	F (4, 24) = 10.14, p <0.001**	F (8, 24) = 0.895, p = 0.536
Speed Quotient	60	F (2, 24) = 5.531, p = 0.043*	F (4, 24) = 1.344, p = 0.310	F (8, 24) = 0.660, p = 0.720
Open Quotient	60	F (2, 24) = 4.536, p = 0.063	F (4, 24) = 1.368, p = 0.302	F (8, 24) = 0.369, p = 0.738

*Significant at 0.05 level
**Significant at 0.005 level

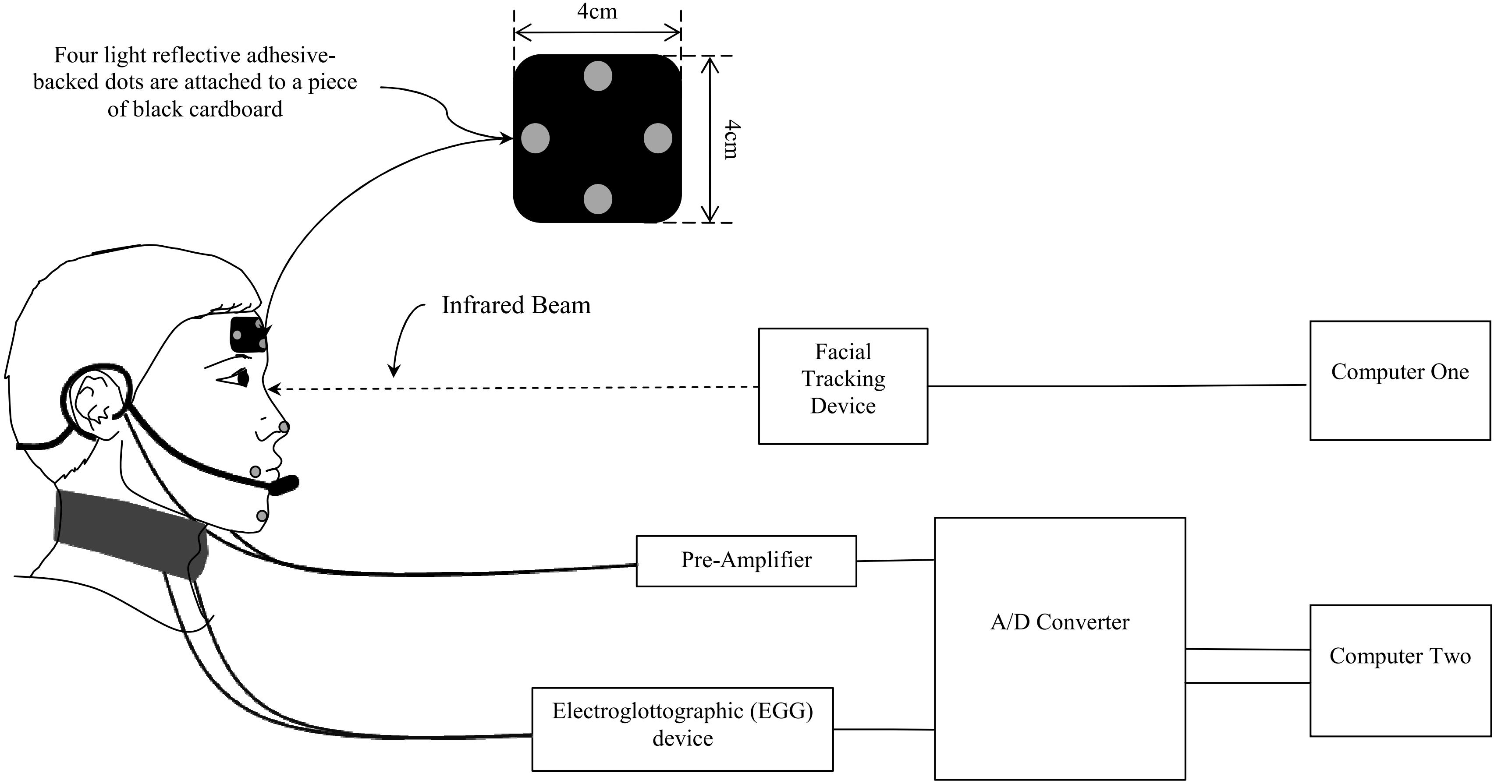


Figure 1. A schematic representation of the instrumental setup for the recording of acoustical, electroglottographic (EGG), and facial tracking signals.

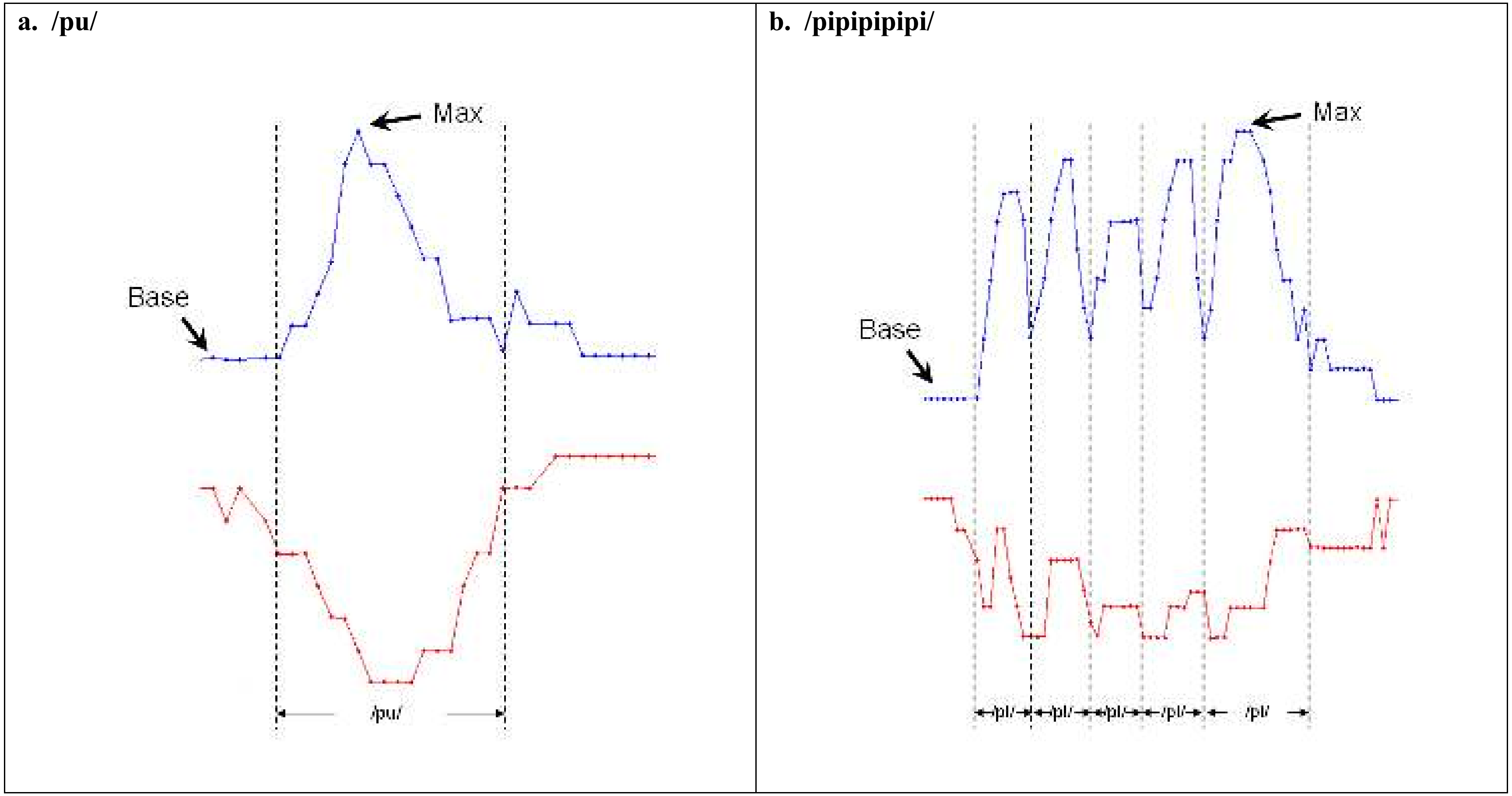
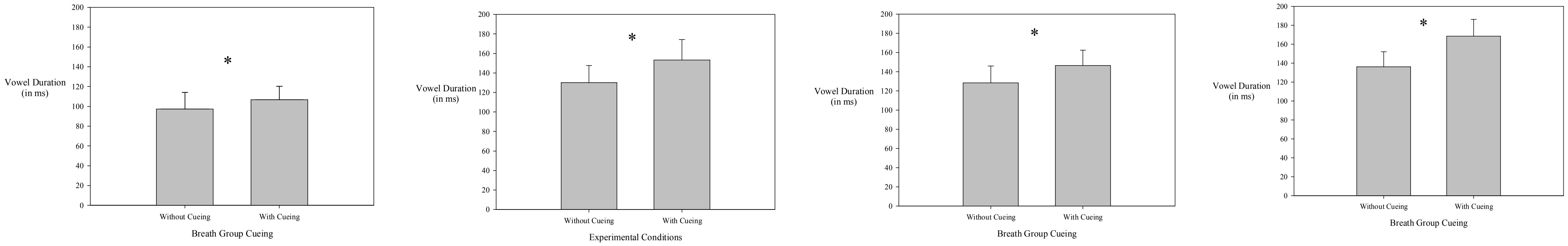


Figure 2. An illustration of the tracings of the extent of lip spreading (lower line) and jaw opening (upper line) with a female control subject's production of /pu/ (on the left) and /pi-pi-pi-pi-pi/ (on the right). The arrow labelled as "Base" marks the baseline level of the jaw at rest preceding the production and the arrow labelled as "Max" marks the maximum displacement of the jaw during production of the single or repeated CV productions.

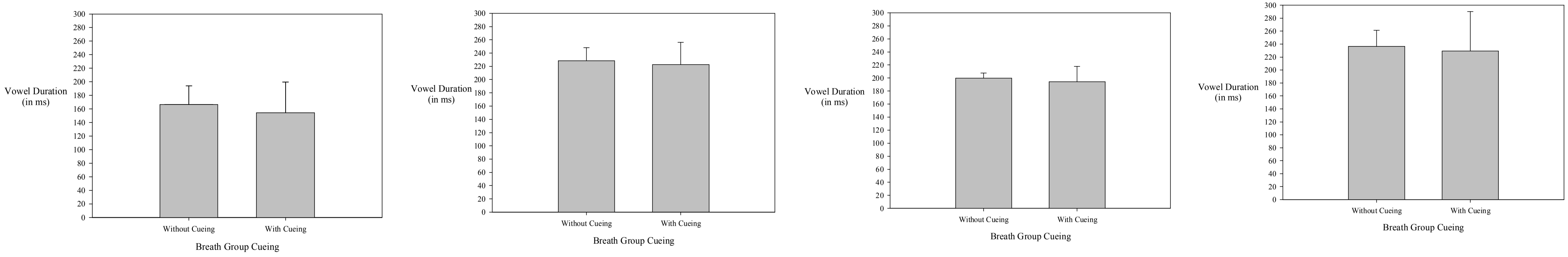


a. Control group - /i/

b. Control group - /a/

c. Control group - /u/

d. Control group - /ɔ/



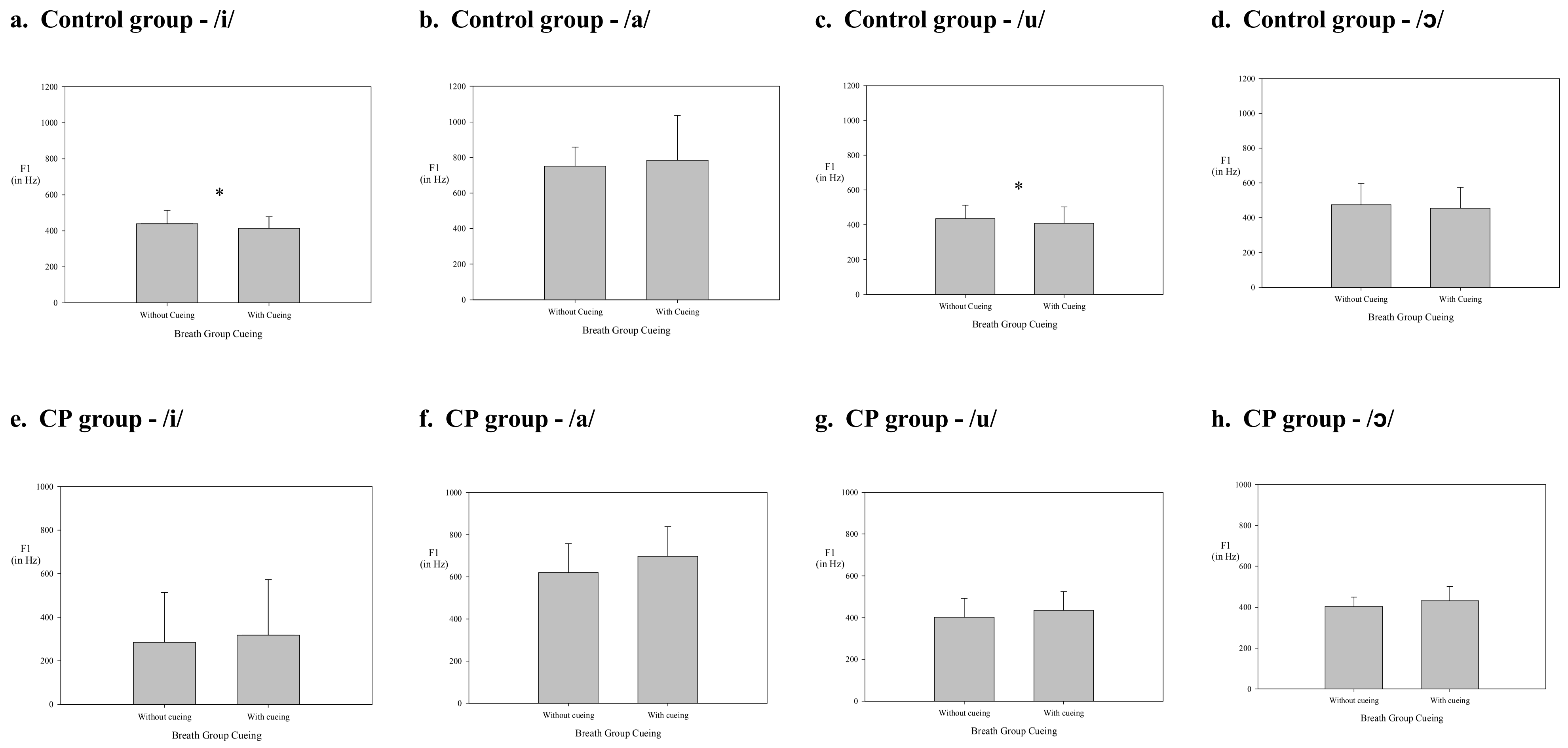
e. CP group - /i/

f. CP group - /a/

g. CP group - /u/

h. CP group - /ɔ/

Figure 3. Means and standard deviations of the measure of vowel duration with and without breath group cueing for the connected speech productions by the control (top graphs) and CP groups (bottom graphs). (Significantly different pairs were marked with “*”.)



a. Control group - /i/

b. Control group - /a/

c. Control group - /u/

d. Control group - /ɔ/

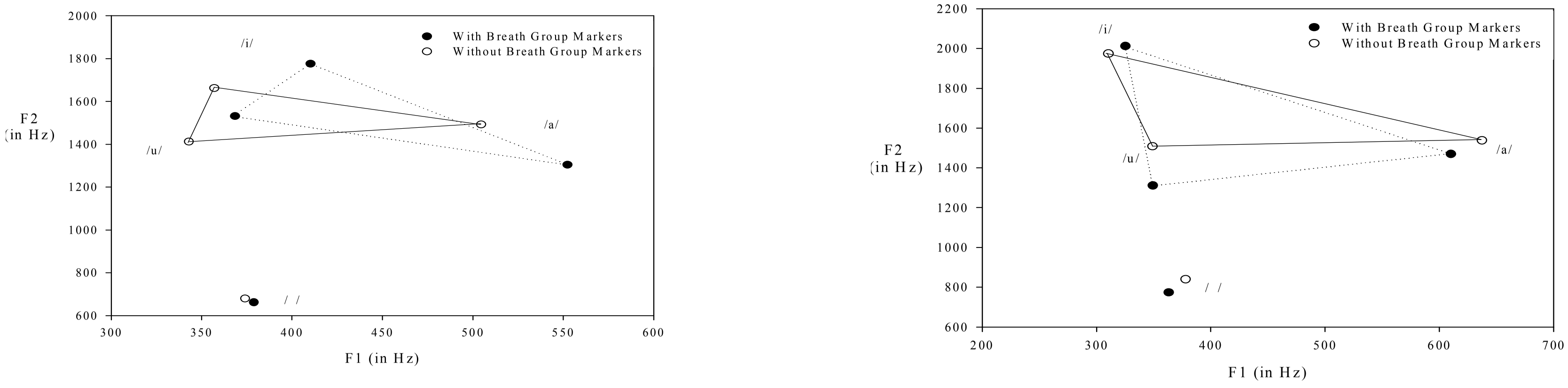
e. CP group - /i/

f. CP group - /a/

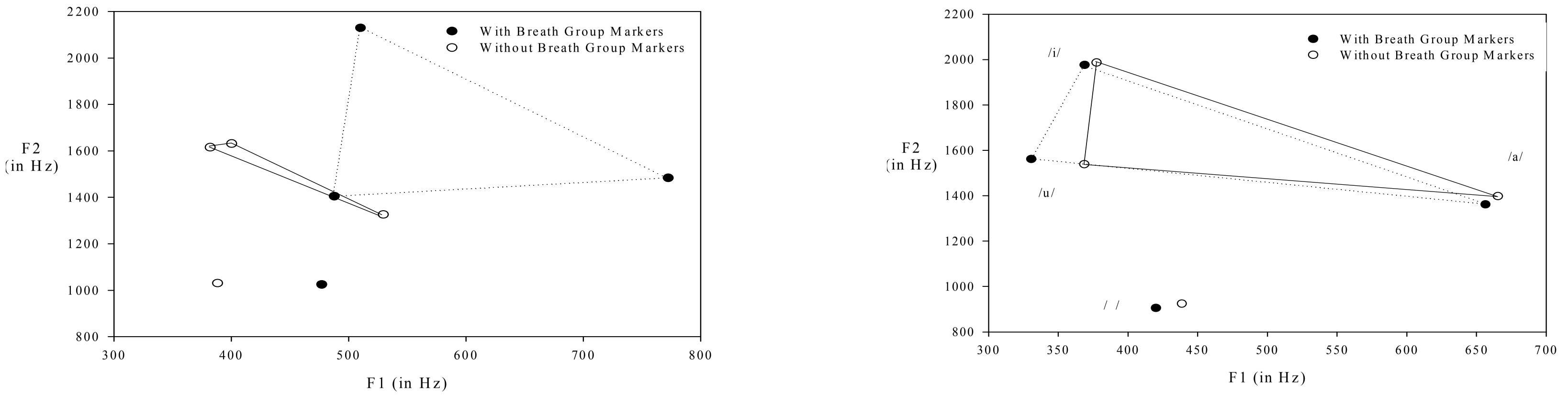
g. CP group - /u/

h. CP group - /ɔ/

Figure 4. Means and standard deviations of the measure of F1 with and without breath group cueing for the connected speech productions by the control (top graphs) and CP groups (bottom graphs). (Significantly different pairs were marked with “*”.)


a. CPM1

b. CPM2


c. CPM3

d. Male Control Group

Figure 5. The vowel working space with and without breath group cueing for the connected speech productions by three CP males, including CPM1 (top left), CPM2 (top right), and CPM3 (bottom left), and the male control group (bottom right).

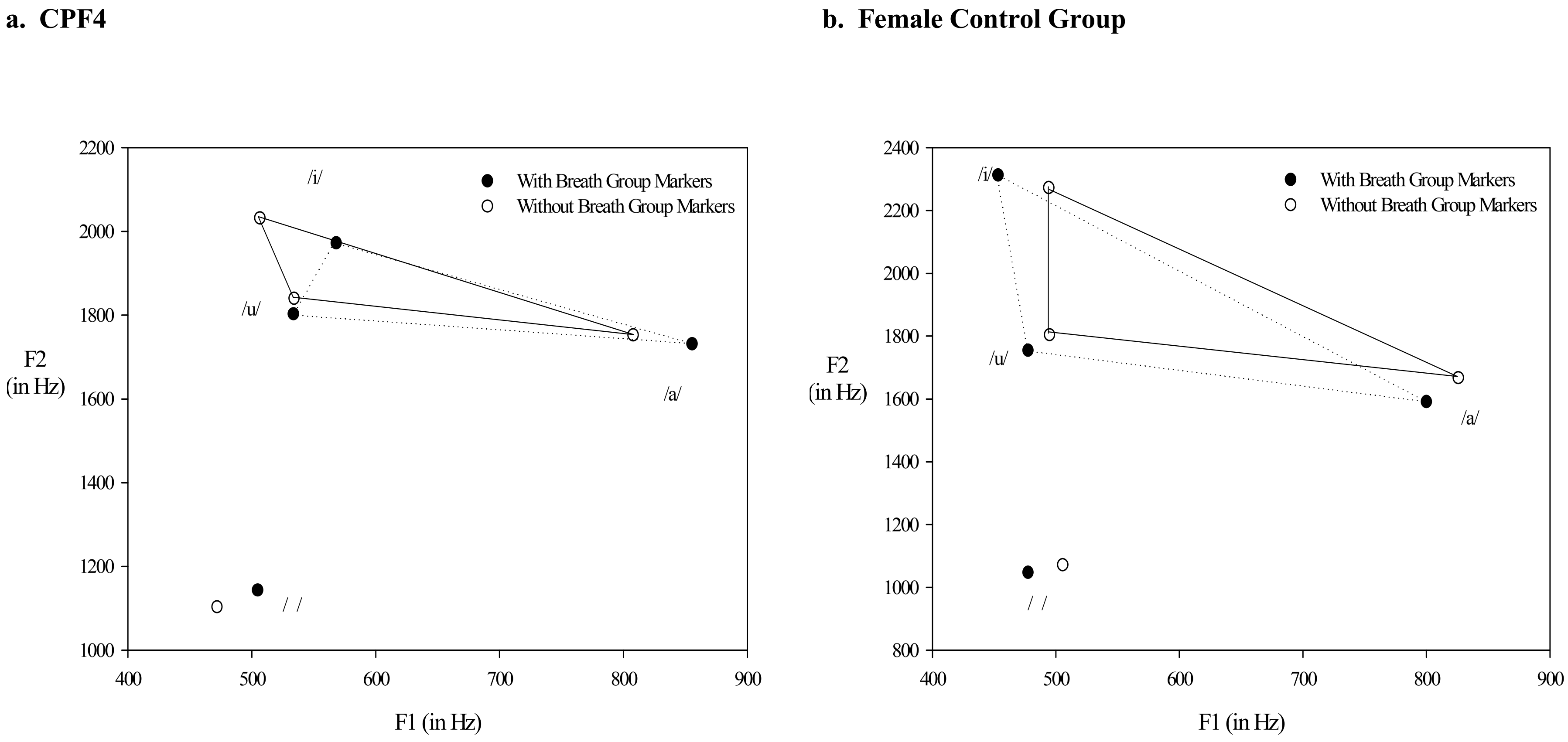


Figure 6. The vowel working space with and without breath group cueing for the connected speech productions by CPF4 (left) and the female control group (right).

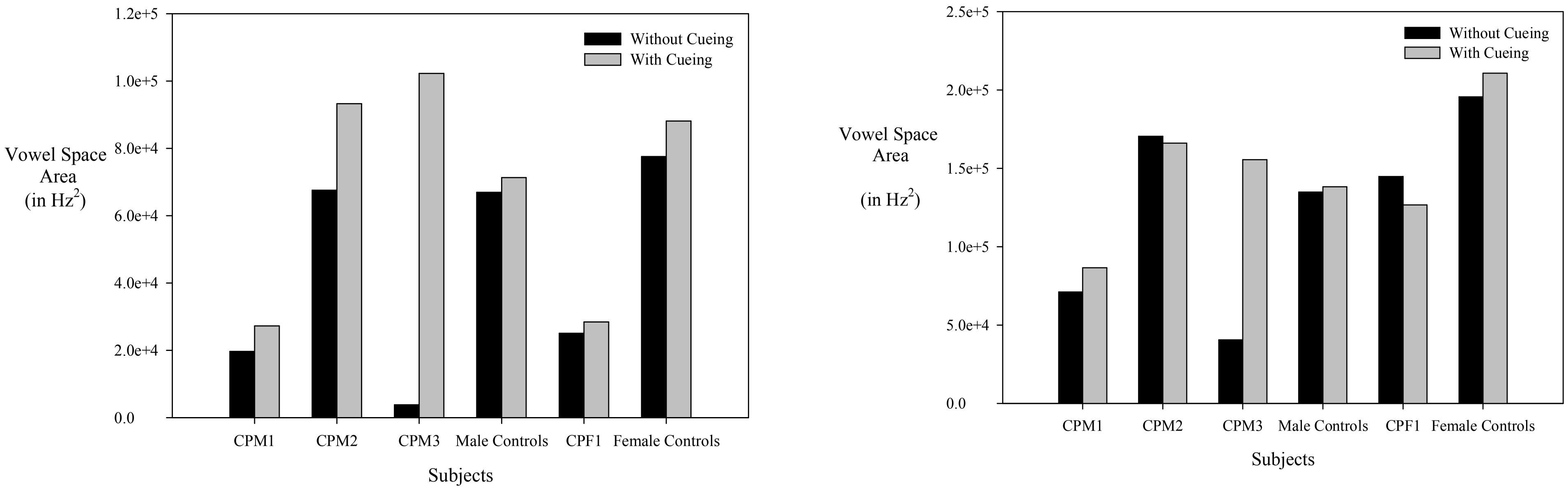
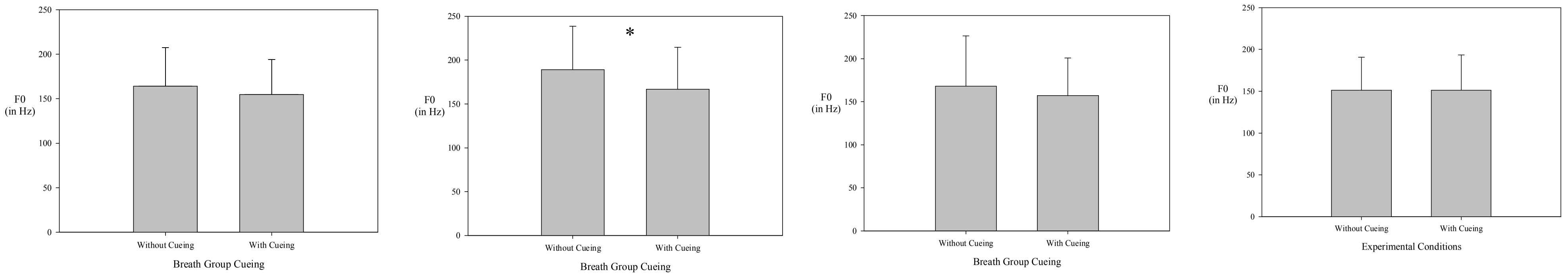


Figure 7. Mean vowel working space area (in Hz^2) with and without cueing for the connected speech productions by four CP subjects (CPM1, CPM2, CPM3, and CPF4) and the control male and female groups derived from the vowels /i/, /a/ and /u/ (left) and /i/, /a/ and /ɔ/.

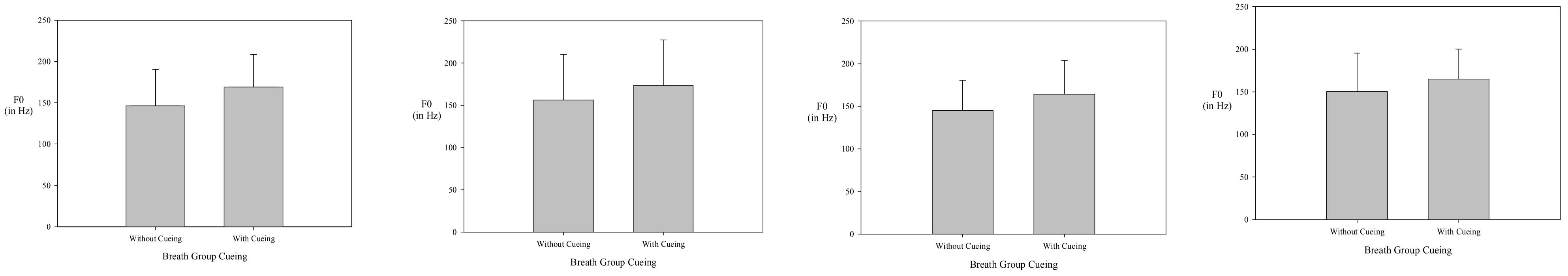


a. Control group - /i/

b. Control group - /a/

c. Control group - /u/

d. Control group - /ɔ/



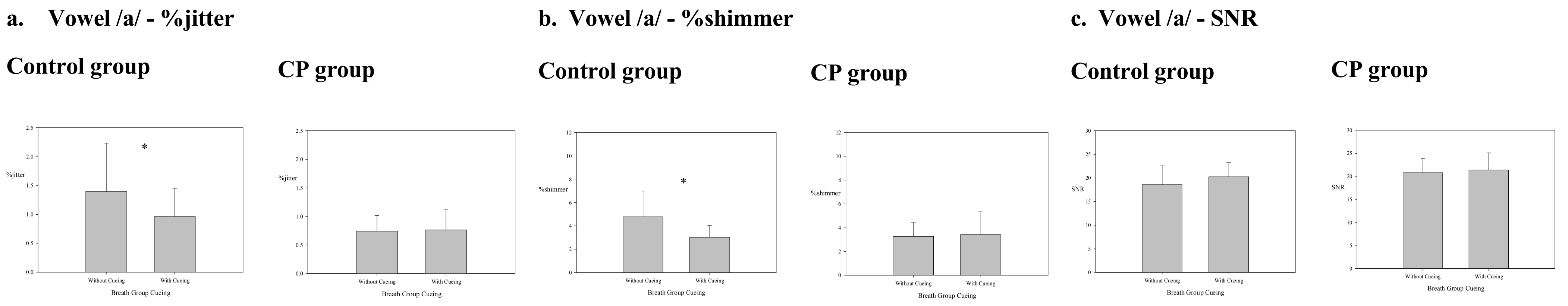
e. CP group - /i/

f. CP group - /a/

g. CP group - /u/

h. CP group - /ɔ/

Figure 8. Means and standard deviations of the measure of F0 with and without breath group cueing for the connected speech productions by the control (top graphs) and CP groups (bottom graphs). (Significantly different pairs were marked with "*".)



a. Vowel /a/ - %jitter

Control group

CP group

b. Vowel /a/ - %shimmer

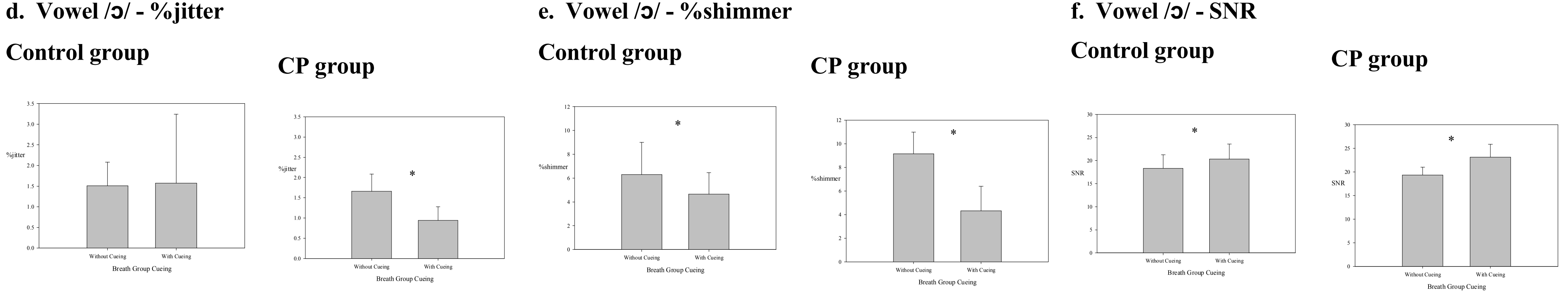
Control group

CP group

c. Vowel /a/ - SNR

Control group

CP group



d. Vowel /ɔ/ - %jitter

Control group

CP group

e. Vowel /ɔ/ - %shimmer

Control group

CP group

f. Vowel /ɔ/ - SNR

Control group

CP group

Figure 9. Means and standard deviations of the measure of %jitter, %shimmer, and SNR with and without breath group cueing for the connected speech productions by the control group in the vowel /u/ and /ɔ/ contexts (top graphs) and the CP group in the vowel /ɔ/ context (bottom graphs). (Significantly different pairs were marked with “*”.)

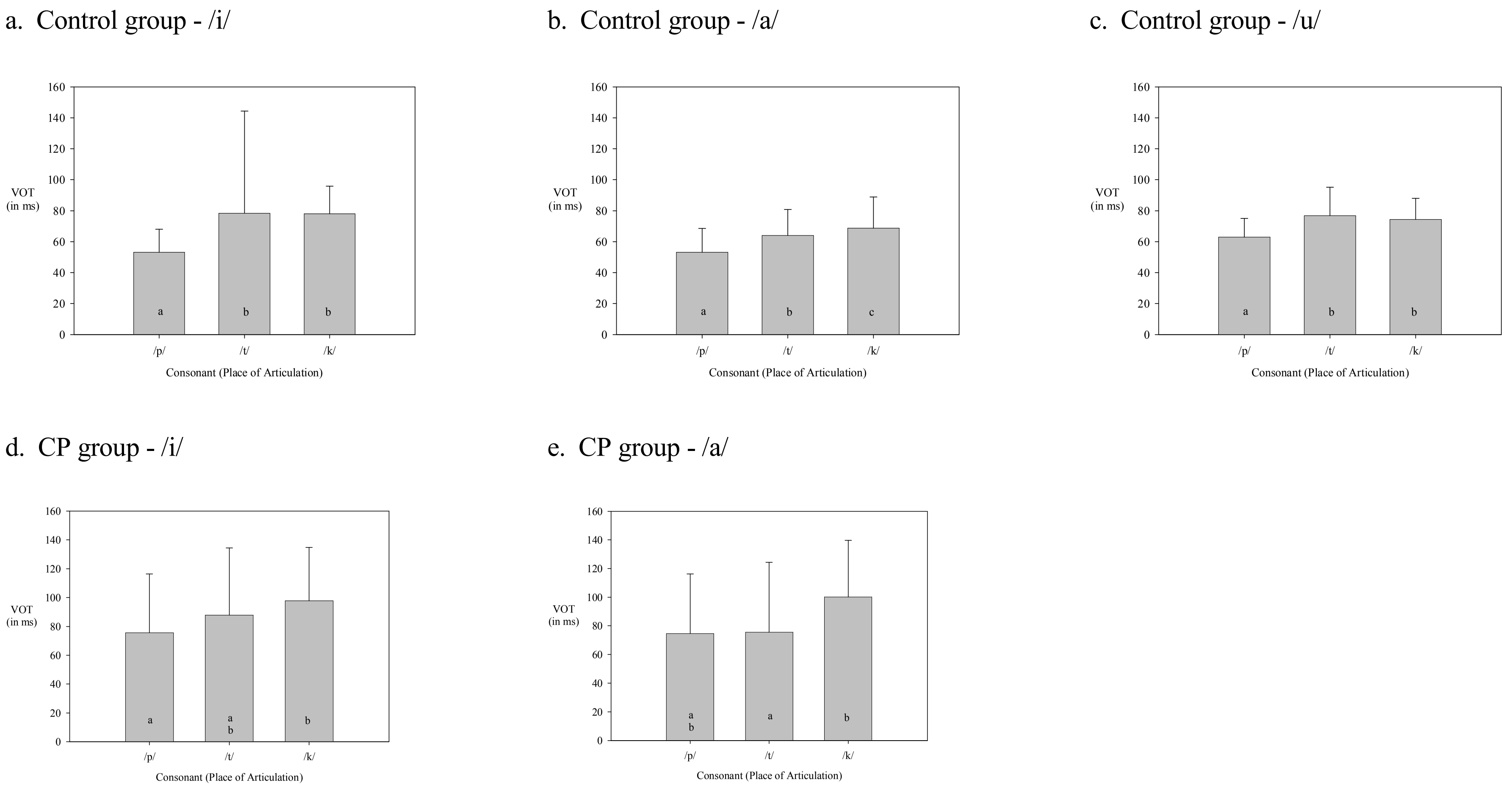
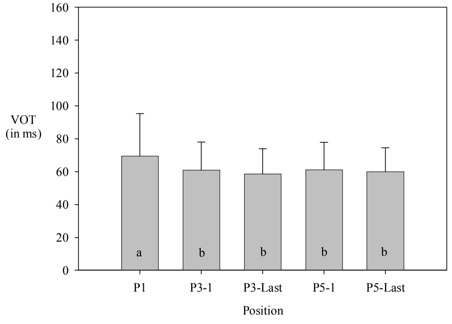


Figure 10. Means and standard deviations of the measure of VOT across consonants for the non-speech productions by the control (top graphs) and CP groups (bottom graphs). (Means significantly different were labelled with different letters.)

a. Control group - /a/



b. CP group - /a/

c. CP group - /u/

Figure 11. Means and standard deviations of the measure of VOT across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by the control (top graph) and CP groups (bottom graphs). (Means significantly different were labelled with different letters.)

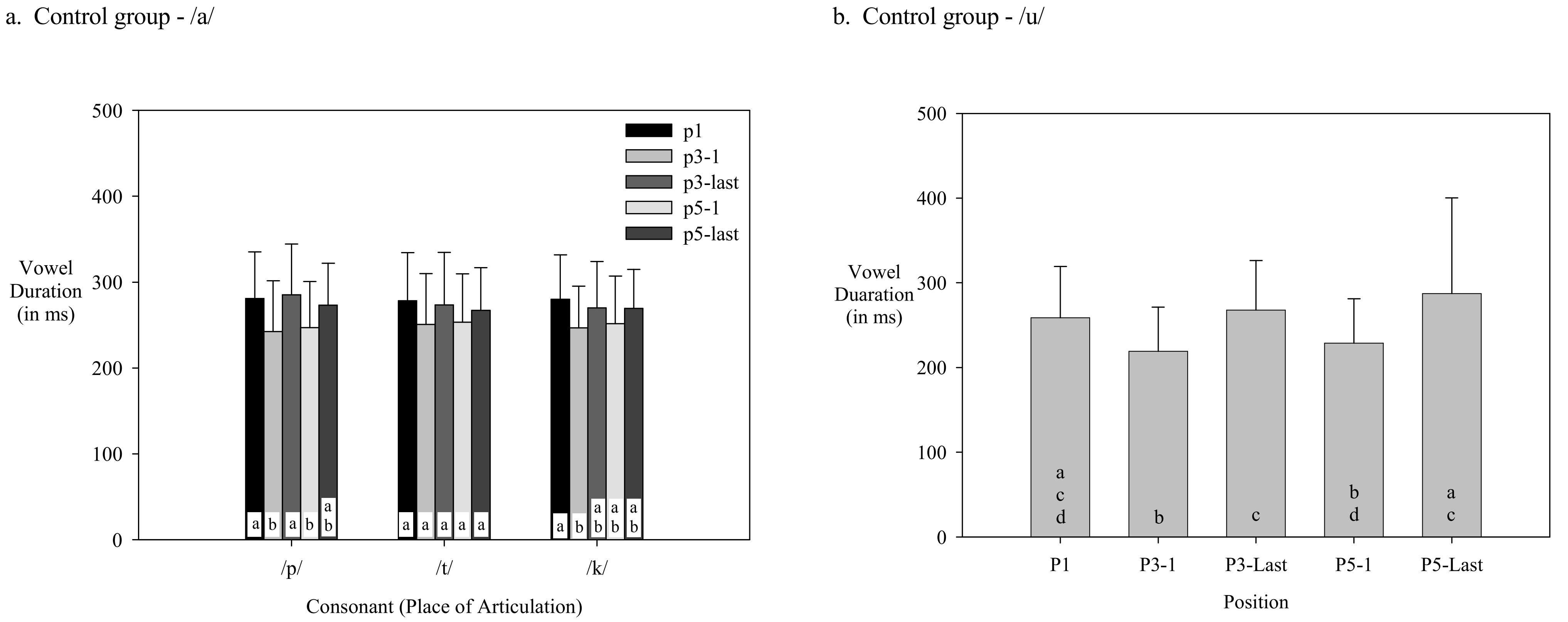


Figure 12. Means and standard deviations of the measure of vowel duration across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by the control group. (Means significantly different were labelled with different letters.)

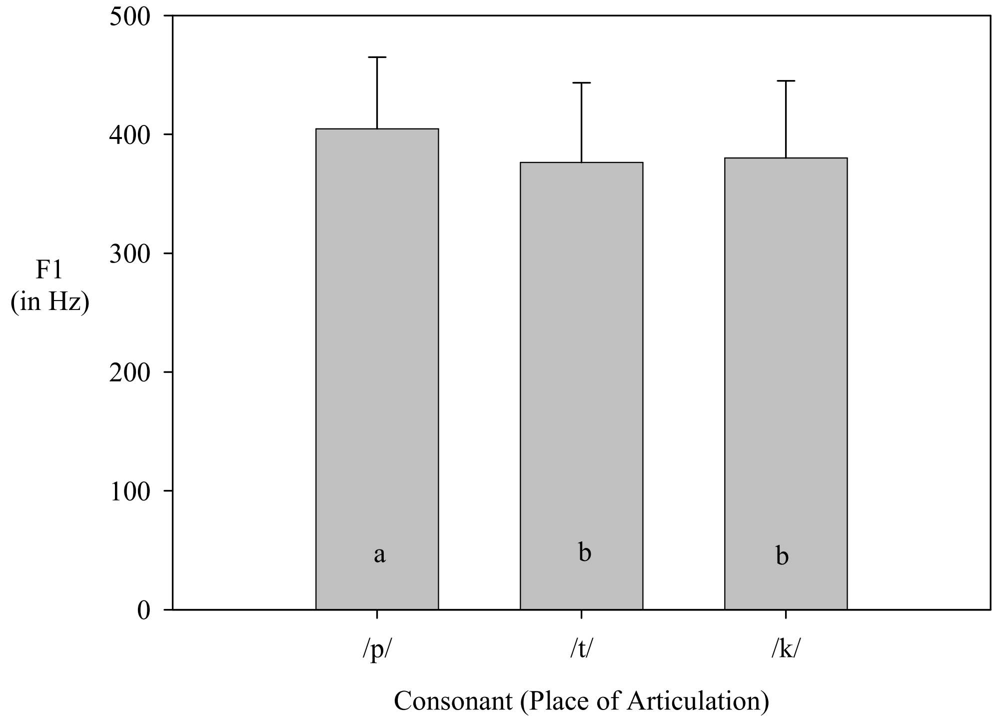
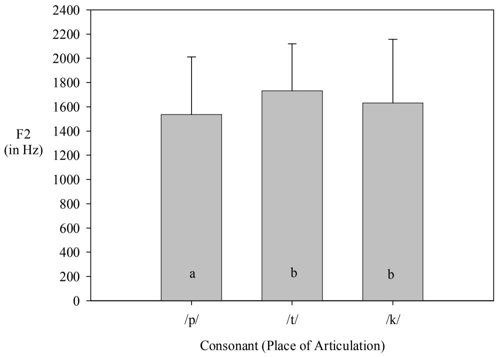
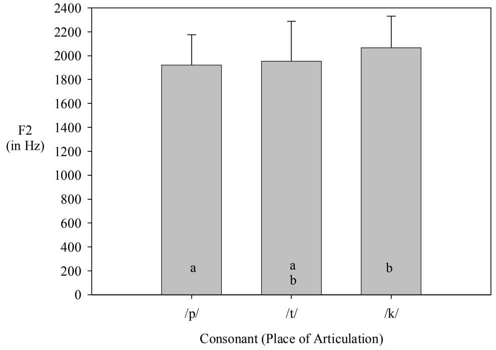


Figure 13. Means and standard deviations of the measure of F1 across consonants for the non-speech productions by the CP group in the vowel /i/ context. (Means significantly different were labelled with different letters.)

a. Control group - /u/



b. CP group - /i/



c. CP group - /a/

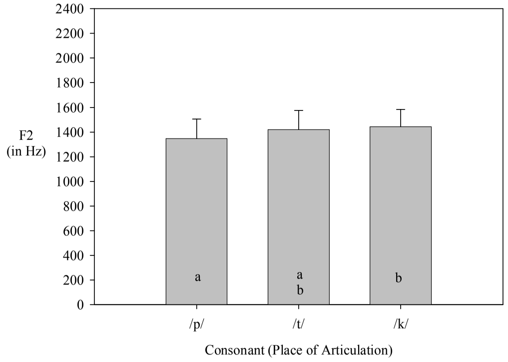
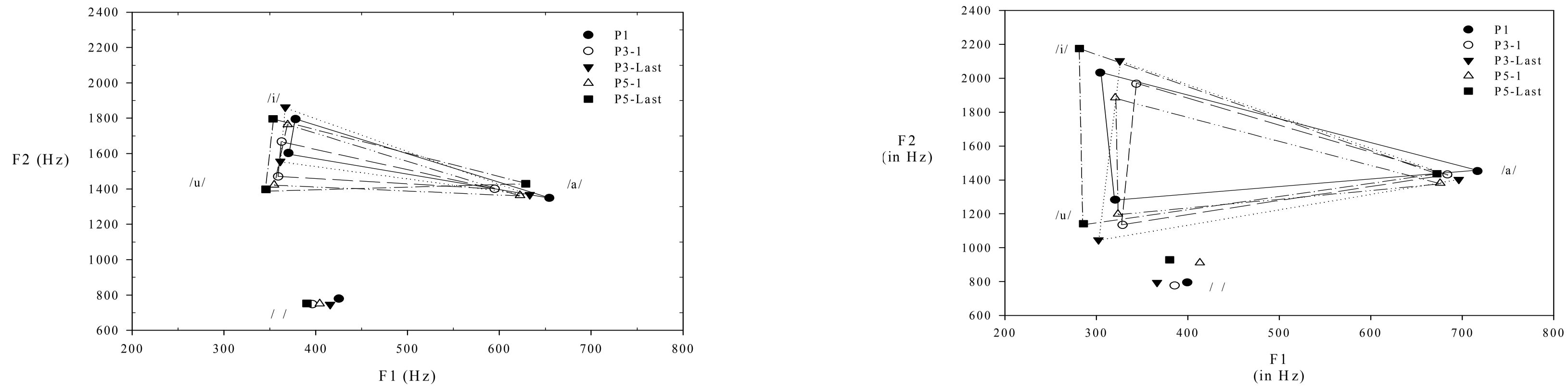


Figure 14. Means and standard deviations of the measure of F2 across consonants for the non-speech productions by the control (top graph) and CP groups (bottom graphs). (Means significantly different were labelled with different letters.)

a. CPM1

b. CPM2



c. CPM3

d. Male control group

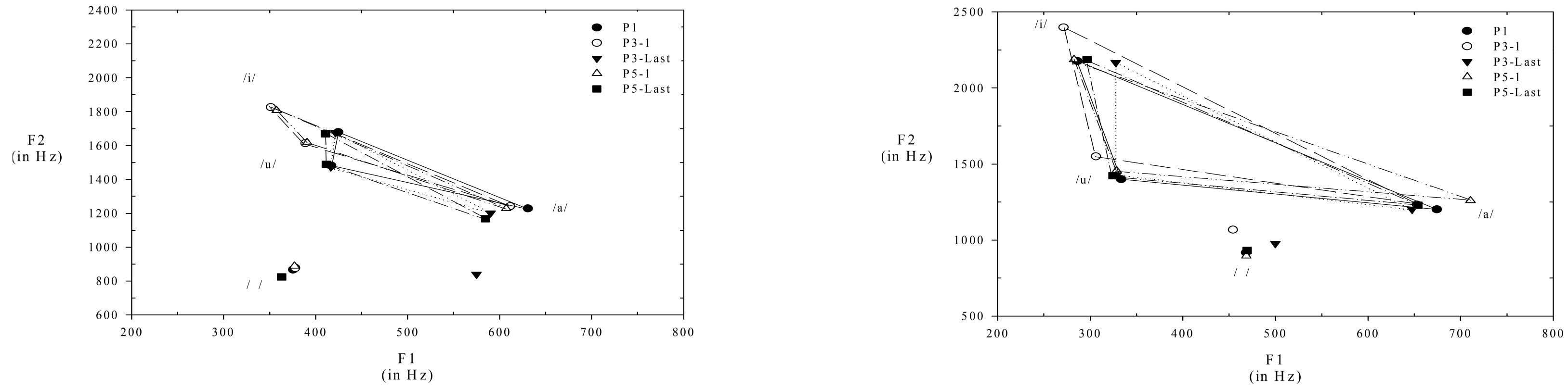
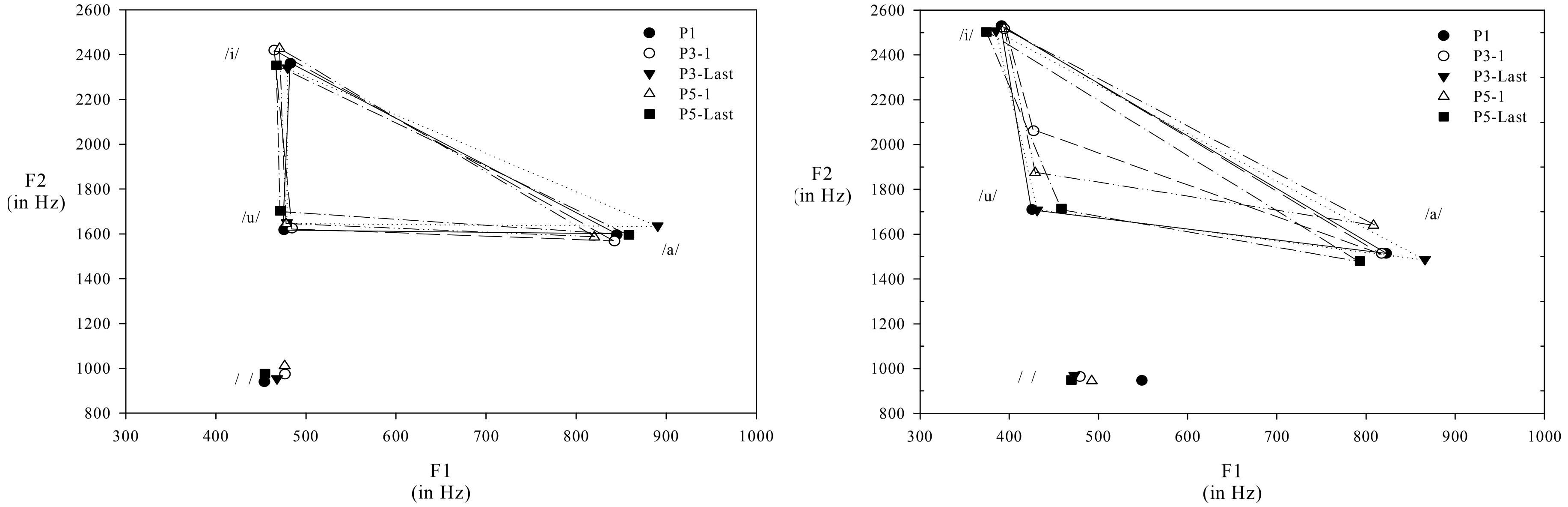


Figure 15. The vowel working space across positions (“p1”: monosyllabic, “p3-1”: first syllable in a 3-syllable train, “p3-last”: last syllable in a 3-syllable train, “p5-1”: first syllable in a 5-syllable train, “p5-last”: last syllable in a 5-syllable train) for the non-speech productions by three CP males, including CPM1 (top left), CPM2 (top right), and CPM3 (bottom left), and the male control group (bottom right).


a. CPF4

b.Female Control Group

Figure 16. The vowel working space across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by CPF4 (left) and the female control group (right).

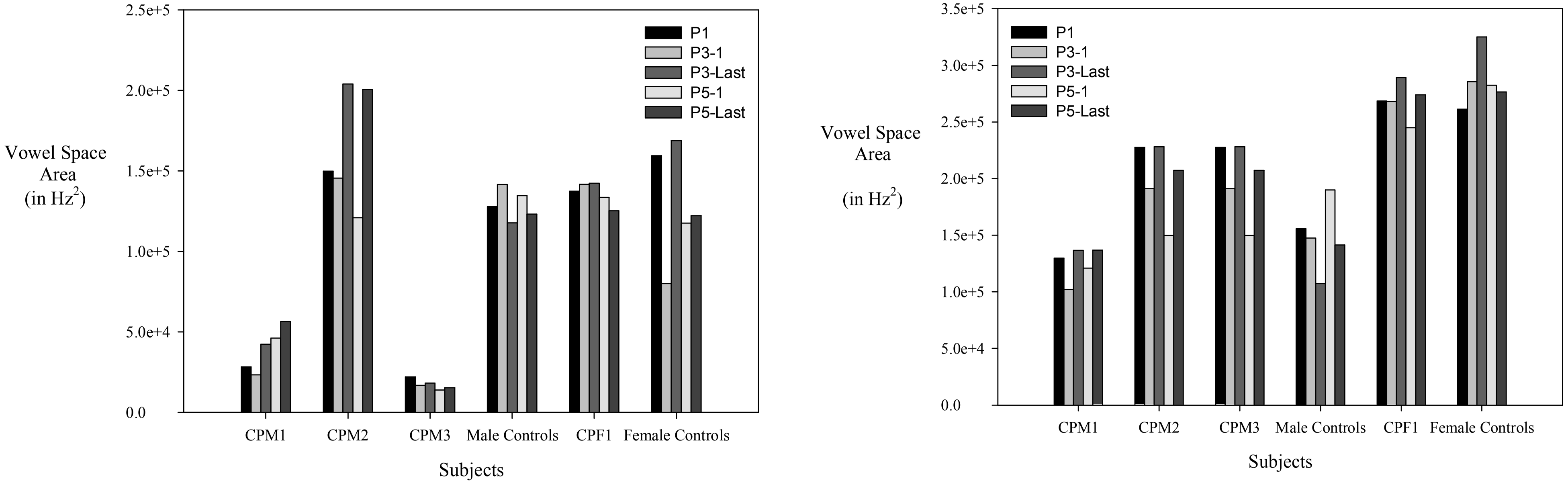
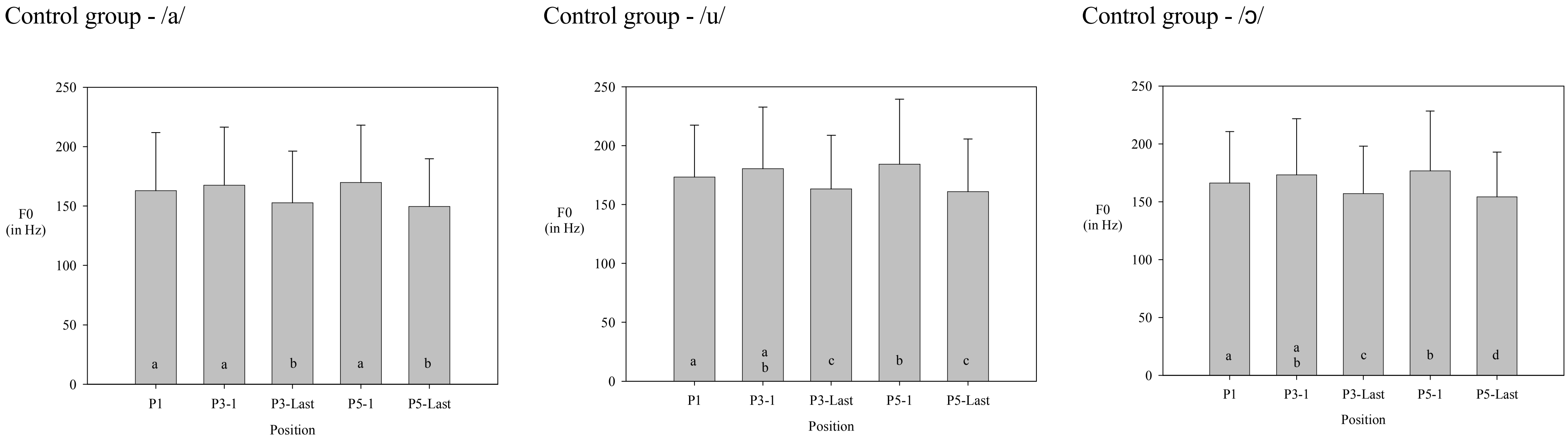


Figure 17. Mean vowel working space area (in Hz^2) across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by four CP subjects (CPM1, CPM2, CPM3, and CPF4) and the control male and female groups derived from the vowels /i/, /a/ and /u/ (left) and /i/, /a/ and /ɔ/.



Control group - /a/

Control group - /u/

Control group - /ɔ/

Figure 18. Means and standard deviations of the measure of F0 across positions (“p1”: monosyllabic, “p3-1”: first syllable in a 3-syllable train, “p3-last”: last syllable in a 3-syllable train, “p5-1”: first syllable in a 5-syllable train, “p5-last”: last syllable in a 5-syllable train) for the non-speech productions by the control group. (Means significantly different were labelled with different letters.)

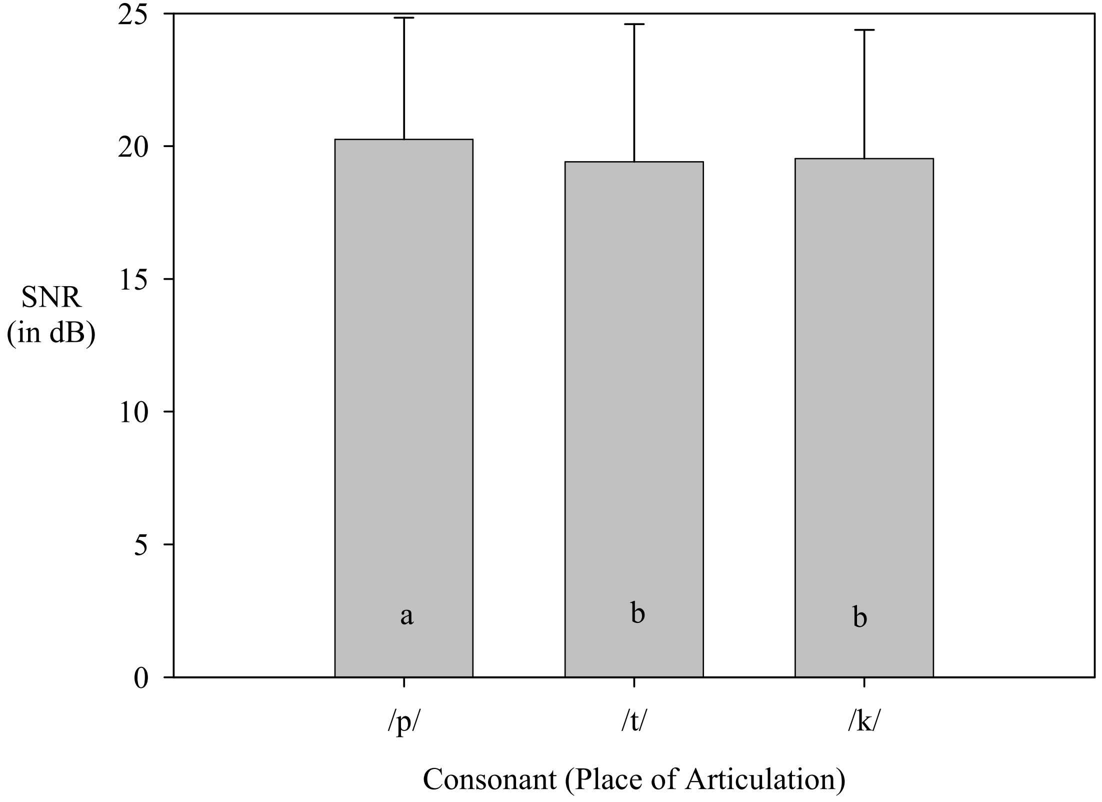


Figure 19. Means and standard deviations of the measure of SNR across consonants for the non-speech productions by the control group in the vowel /a/ context. (Means significantly different were labelled with different letters.)

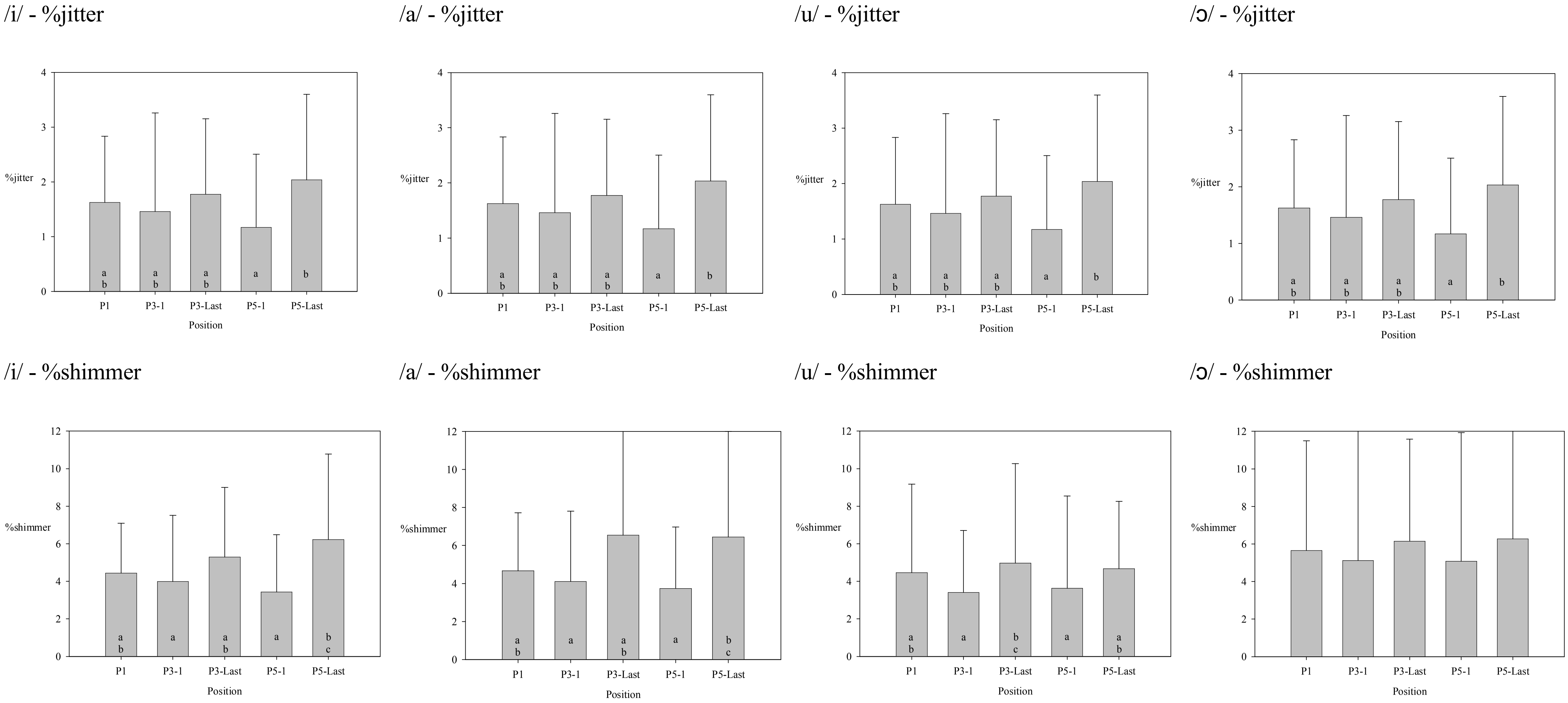


Figure 20. Means and standard deviations of the measure of %jitter (top graphs) and %shimmer (bottom graphs) across positions (“p1”: monosyllabic, “p3-1”: first syllable in a 3-syllable train, “p3-last”: last syllable in a 3-syllable train, “p5-1”: first syllable in a 5-syllable train, “p5-last”: last syllable in a 5-syllable train) for the non-speech productions by the control group. (Means significantly different were labelled with different letters.)

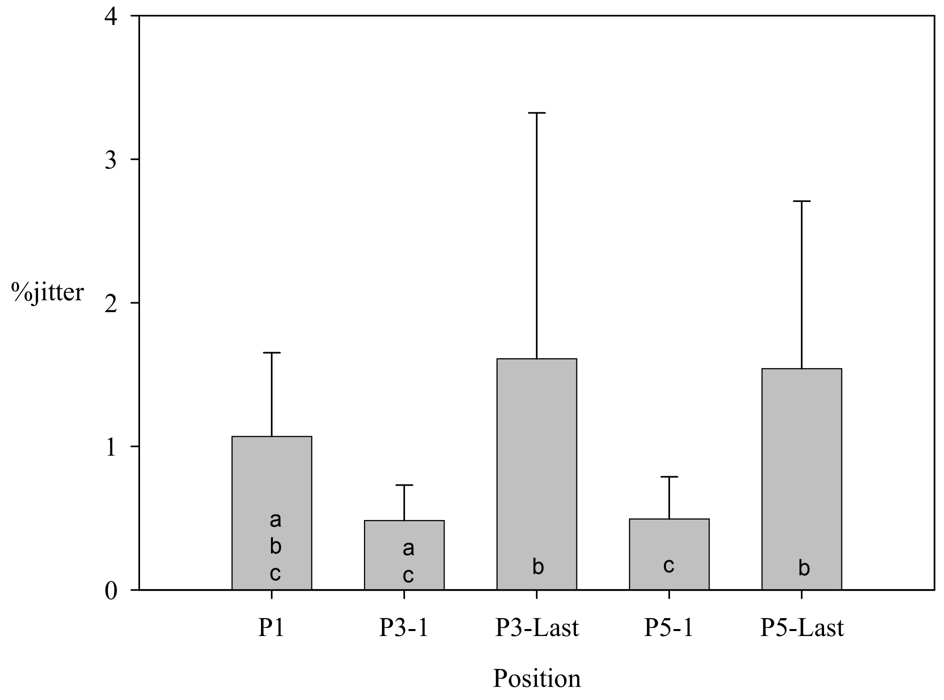
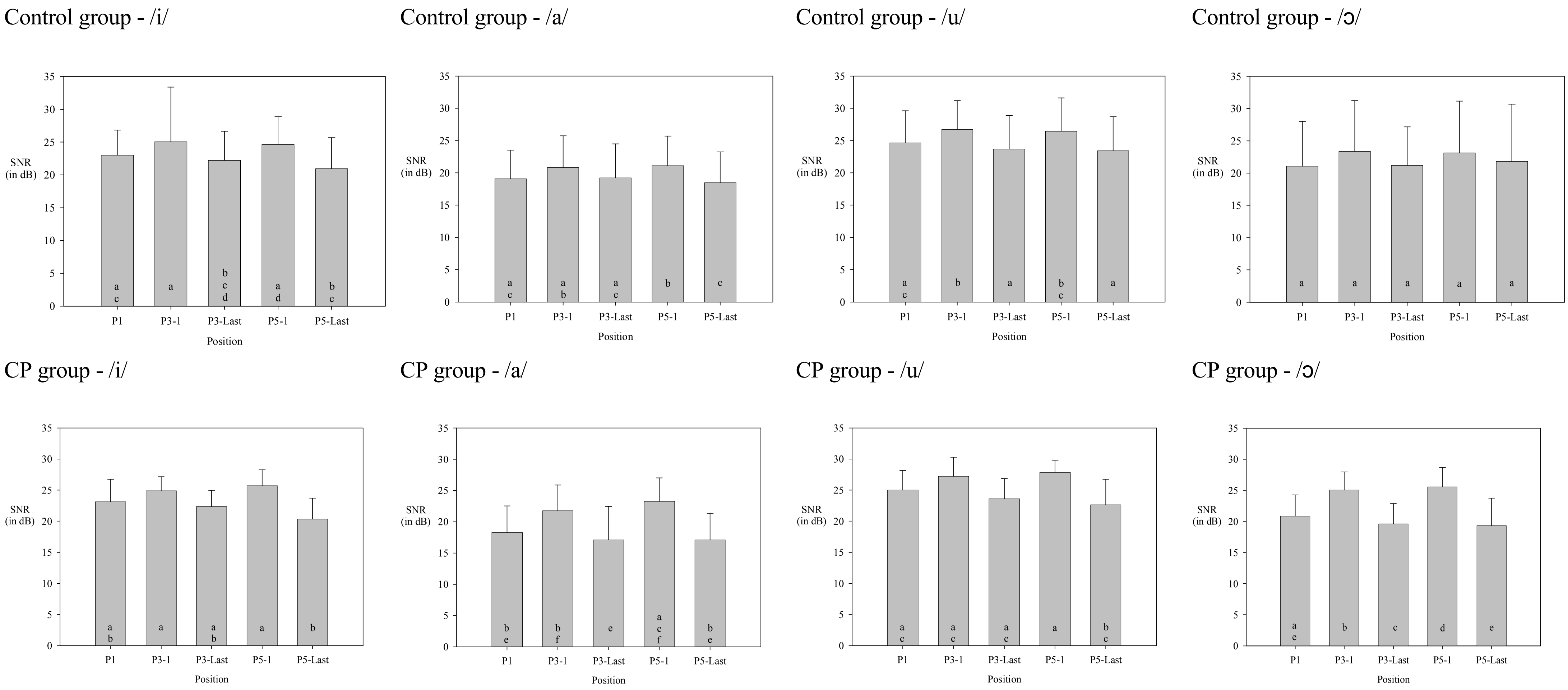


Figure 21. Means and standard deviations of the measure of %jitter across positions (“p1”: monosyllabic, “p3-1”: first syllable in a 3-syllable train, “p3-last”: last syllable in a 3-syllable train, “p5-1”: first syllable in a 5-syllable train, “p5-last”: last syllable in a 5-syllable train) for the non-speech productions by the CP group in the vowel /ɔ/ context. (Means significantly different were labelled with different letters.)



Control group - /i/

Control group - /a/

Control group - /u/

Control group - /ɔ/

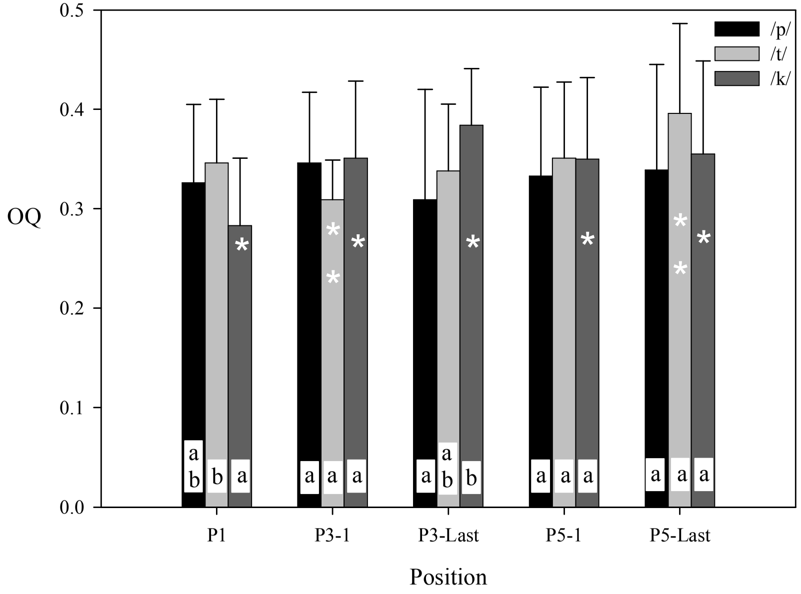
CP group - /i/

CP group - /a/

CP group - /u/

CP group - /ɔ/

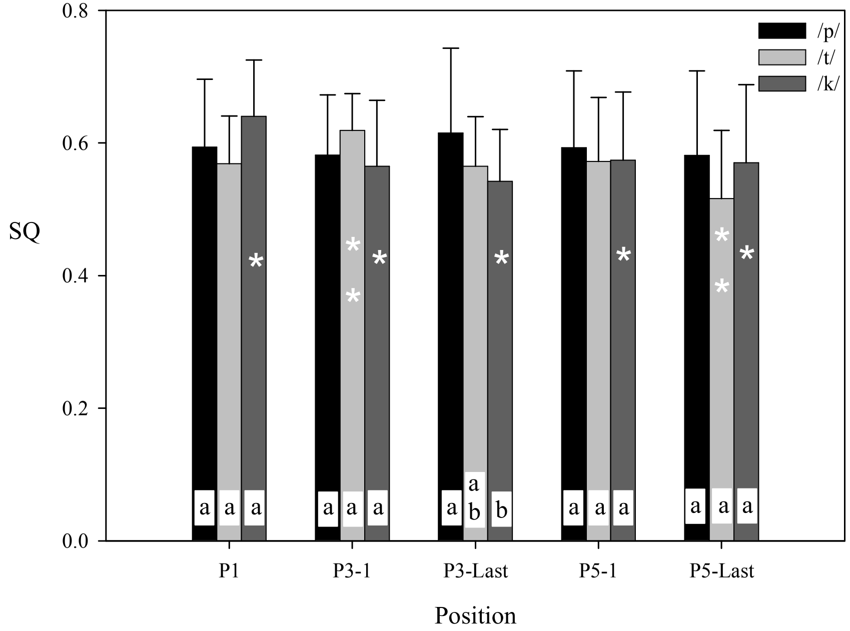
Figure 22. Means and standard deviations of the measure of SNR across positions (“p1”: monosyllabic, “p3-1”: first syllable in a 3-syllable train, “p3-last”: last syllable in a 3-syllable train, “p5-1”: first syllable in a 5-syllable train, “p5-last”: last syllable in a 5-syllable train) for the non-speech productions by the control (top graphs) and CP (bottom graphs) groups. (Means significantly different were labelled with different letters.)



*In the /k/ context, P1 is significantly lower than all the other positions.

**In the /t/ context, P3-1 is significantly lower than P5-last.

Figure 23. Means and standard deviations of OQ across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by the control group in the vowel /ɔ/ context. (Means significantly different were labelled with different letters.)



*In the /k/ context, P1 is significantly higher than all the other positions;

**In the /t/ context, P3-1 is significantly higher than P5-last.

Figure 24. Means and standard deviations of SQ across positions ("p1": monosyllabic, "p3-1": first syllable in a 3-syllable train, "p3-last": last syllable in a 3-syllable train, "p5-1": first syllable in a 5-syllable train, "p5-last": last syllable in a 5-syllable train) for the non-speech productions by the control group in the vowel /ɔ/ context. (Means significantly different were labelled with different letters.)

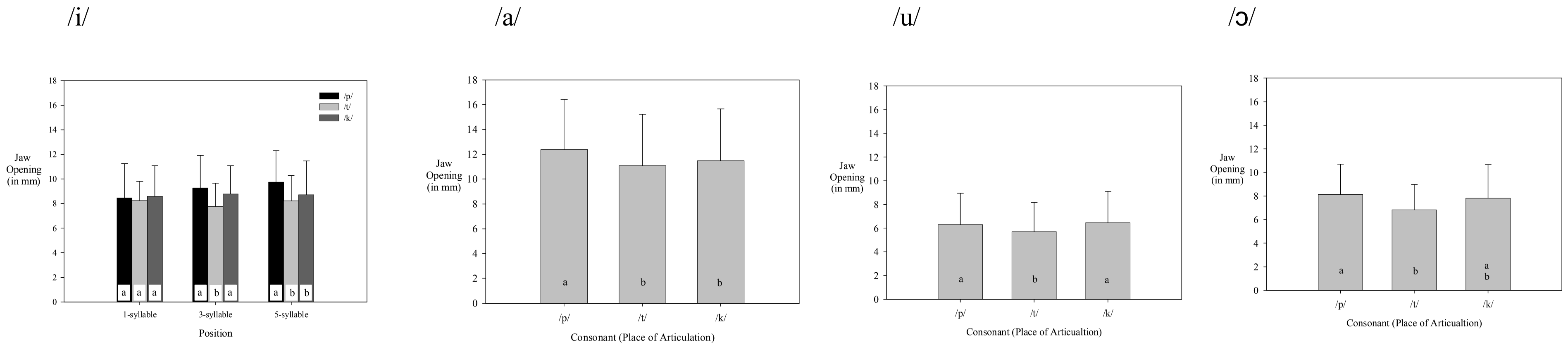


Figure 25. Means and standard deviations of the measure of maximum jaw displacement (jaw opening) across consonants (for /a/, /u/, and /ɔ/) or across consonants for each breath group length (for /i/) for the non-speech productions by the control group. (Means significantly different were labelled with different letters.)

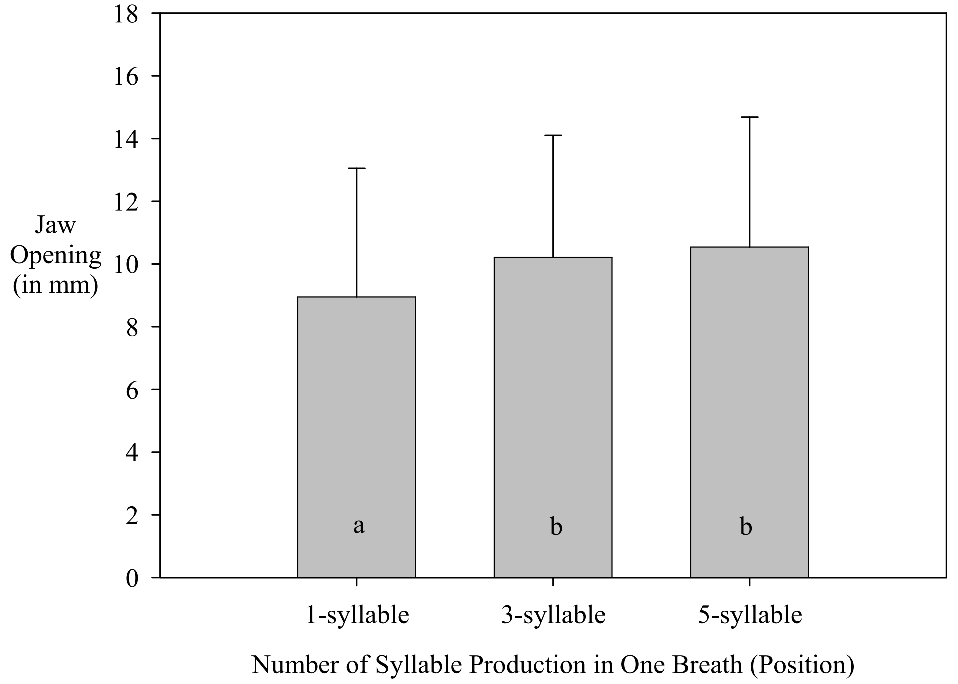


Figure 26. Means and standard deviations of the measure of maximum jaw displacement (jaw opening) across positions for the non-speech productions by the CP group in the vowel /i/ context. (Means significantly different were labelled with different letters.)

Appendix 1

Subject Information for Individuals in the control group

Participant	Age	Gender	Native Language
NF1	22	F	New Zealand English
NF2	21	F	New Zealand English
NF3	22	F	New Zealand English
NF4	24	F	New Zealand English
NM5	21	M	New Zealand English
NM6	27	M	British English
NM7	43	M	American English
NF8	38	F	American English
NF9	44	F	New Zealand English
NM10	24	M	New Zealand English
NF11	25	F	New Zealand English
NM12	31	M	New Zealand English
NM13	33	M	New Zealand English
NF14	40	F	New Zealand English
NM15	38	M	New Zealand English
NM16	40	M	New Zealand English

Appendix 2

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the control group – vowel duration

Subject	N	t	df	p
/i/				
NF1	20	-3.951	18	<0.001**
NF2	20	-3.320	18	0.004**
NF3	20	-0.000195	18	1.000
NF4	20	-2.759	18	0.013*
NM5	18[†]	-0.889	16	0.387
NM6	---	---	---	---
NM7	20	2.214	18	0.040*
NF8	20	-4.789	18	<0.001**
NF9	20	-2.563	18	0.020*
NM10	20	-0.565	18	0.579
NF11	20	-2.104	18	0.050*
NM12	20	-0.874	18	0.394
NM13	20	-0.348	18	0.732
NF14	20	-3.054	18	0.007**
NM15	20	-2.548	18	0.020*
NM16	20	-0.480	18	0.637
/a/				
NF1	20	-3.180	18	0.005**
NF2	20	-1.918	18	0.071
NF3	20	-0.450	18	0.658
NF4	20	-1.706	18	0.105
NM5	18[†]	-2.151	16	0.047
NM6	---	---	---	---
NM7	20	-1.402	18	0.178
NF8	20	-1.531	18	0.143
NF9	20	-1.820	18	0.085
NM10	20	-3.011	18	0.008*
NF11	20	-3.393	18	0.003**
NM12	20	-6.439	18	<0.001**
NM13	20	-0.525	18	0.606
NF14	20	0.319	18	0.754
NM15	20	-2.918	18	0.009*
NM16	20	-2.974	18	0.008*
/u/				
NF1	20	-2.132	18	0.047*
NF2	20	-0.995	18	0.333
NF3	20	-1.146	18	0.267
NF4	20	-0.402	18	0.693
NM5	18[†]	-1.096	16	0.289
NM6	---	---	---	---
NM7	20	-0.366	18	0.719
NF8	20	-1.742	18	0.099
NF9	20	-1.813	18	0.086
NM10	20	-0.799	18	0.435
NF11	20	-1.393	18	0.181
NM12	20	-1.353	18	0.193
NM13	20	0.821	18	0.422
NF14	20	-1.122	18	0.277
NM15	20	-1.820	18	0.085
NM16	20	-0.593	18	0.561
/T/				
NF1	30	-1.363	28	0.184
NF2	30	-1.321	28	0.197
NF3	30	-0.660	28	0.515
NF4	30	-1.794	28	0.084
NM5	27[†]	-1.802	25	0.084
NM6	---	---	---	---
NM7	30	-0.744	28	0.463
NF8	30	-2.415	28	0.023*
NF9	30	-2.484	28	0.019*
NM10	30	-3.158	28	0.004**
NF11	30	-3.509	28	0.002**
NM12	30	-1.976	28	0.058
NM13	30	-2.341	28	0.027*
NF14	30	-1.893	28	0.069
NM15	30	-1.890	28	0.069
NM16	30	-1.381	28	0.178

*Significant at 0.05 level
**Significant at 0.005 level
[†] Missing data

Appendix 3

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the CP group – vowel duration

Subject	N	t	df	P
/i/				
CPM1	20	-1.080	18	0.294
CPM2	20	-0.151	18	0.882
CPM3	20	4.017	18	< 0.001**
CPF4	20	1.523	18	0.145
/a/				
CPM1	20	0.615	18	0.546
CPM2	20	-1.728	18	0.101
CPM3	20	1.080	18	0.295
CPF4	20	1.474	18	0.158
/u/				
CPM1	20	-0.339	18	0.738
CPM2	20	-1.609	18	0.125
CPM3	20	1.668	18	0.113
CPF4	20	1.022	18	0.320
/T/				
CPM1	30	-0.590	28	0.560
CPM2	30	-2.089	28	0.046*
CPM3	30	2.427	28	0.022*
CPF4	30	1.785	28	0.085

*Significant at 0.05 level
**Significant at 0.005 level

Appendix 4

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the control group – F1

Subject	N	t	df	p
/i/				
NF1	20	2.948	18	0.009**
NF2	20	3.528	18	0.002**
NF3	20	1.187	18	0.251
NF4	20	-0.596	18	0.559
NM5	18[†]	1.225	16	0.238
NM6	---	---	---	---
NM7	20	0.460	18	0.651
NF8	20	-0.564	18	0.580
NF9	20	2.203	18	0.041*
NM10	20	1.639	18	0.119
NF11	20	4.911	18	<0.001**
NM12	20	1.225	18	0.236
NM13	20	-1.035	18	0.314
NF14	20	1.482	18	0.156
NM15	20	-1.558	18	0.137
NM16	20	0.727	18	0.476
/a/				
NF1	20	5.221	18	<0.001**
NF2	20	-0.420	18	0.679
NF3	20	2.287	18	0.035*
NF4	20	-1.043	18	0.311
NM5	18[†]	-0.423	16	0.678
NM6	---	---	---	---
NM7	20	1.093	18	0.289
NF8	20	0.344	18	0.735
NF9	20	1.702	18	0.106
NM10	20	0.577	18	0.571
NF11	20	0.667	18	0.513
NM12	20	-0.973	18	0.343
NM13	20	-0.675	18	0.508
NF14	20	0.618	18	0.544
NM15	20	1.333	18	0.199
NM16	20	2.651	18	0.016
/u/				
NF1	20	-0.783	18	0.444
NF2	20	0.555	18	0.586
NF3	20	1.398	18	0.179
NF4	20	0.202	18	0.842
NM5	18[†]	0.519	16	0.611
NM6	---	---	---	---
NM7	20	2.646	18	0.016*
NF8	20	-2.403	18	0.027*
NF9	20	-0.806	18	0.403
NM10	20	1.960	18	0.066
NF11	20	8.298	18	<0.001**
NM12	20	3.010	18	0.008*
NM13	20	3.395	18	0.003**
NF14	20	-0.388	18	0.703
NM15	20	0.956	18	0.352
NM16	20	0.273	18	0.788
/ɔ/				
NF1	30	0.748	28	0.461
NF2	30	-0.774	28	0.445
NF3	30	-1.659	28	0.108
NF4	30	-2.503	28	0.018*
NM5	27[†]	-2.439	25	0.022*
NM6	---	---	---	---
NM7	30	0.323	28	0.749
NF8	30	0.225	28	0.824
NF9	30	-1.783	28	0.085
NM10	30	3.523	28	0.001**
NF11	30	1.538	28	0.135
NM12	30	1.770	28	0.088
NM13	30	1.408	28	0.170
NF14	30	-0.251	28	0.804
NM15	30	-1.454	28	0.157
NM16	30	1.855	28	0.074

*Significant at 0.05 level

**Significant at 0.005 level

[†]Missing data

Appendix 5

Results of t tests on the "breath group cueing" effect for the connected speech data from individuals in the CP group – F1

Subject	N	t	df	P
/i/				
CPM1	20	-1.703	18	0.106
CPM2	20	-1.371	18	0.187
CPM3	20	1.414	18	0.174
CPF4	20	-2.590	18	0.018*
/a/				
CPM1	20	-1.809	18	0.087
CPM2	20	0.838	18	0.413
CPM3	20	-11.493	18	<0.001**
CPF4	20	-2.338	18	0.031*
/u/				
CPM1	20	-2.031	18	0.057
CPM2	20	-0.0237	18	0.981
CPM3	20	-3.831	18	0.001**
CPF4	20	0.0151	18	0.988
/ɔ/				
CPM1	30	-0.317	28	0.754
CPM2	30	1.008	28	0.322
CPM3	30	-6.017	28	<0.001**
CPF4	30	-1.527	28	0.138

*Significant at 0.05 level
**Significant at 0.005 level

Appendix 6

Results of t tests on the "breath group cueing" effect for the connected speech data from individuals in the control group – F2

Subject	N	t	df	p
/i/				
NF1	20	-0.582	18	0.568
NF2	20	-4.232	18	<0.001**
NF3	20	0.479	18	0.638
NF4	20	1.145	18	0.267
NM5	18†	-0.274	16	0.787
NM6	---	---	---	---
NM7	20	1.215	18	0.240
NF8	20	0.994	18	0.334
NF9	20	-6.013	18	<0.001**
NM10	20	1.498	18	0.151
NF11	20	0.261	18	0.797
NM12	20	-3.119	18	0.006**
NM13	20	0.981	18	0.340
NF14	20	-0.836	18	0.414
NM15	20	-0.546	18	0.592
NM16	20	-0.445	18	0.661
/a/				
NF1	20	1.767	18	0.094
NF2	20	0.233	18	0.818
NF3	20	-0.728	18	0.476
NF4	20	1.258	18	0.224
NM5	18†	0.880	16	0.392
NM6	---	---	---	---
NM7	20	-0.305	18	0.764
NF8	20	2.876	18	0.010*
NF9	20	-1.289	18	0.214
NM10	20	2.495	18	0.023*
NF11	20	11.844	18	<0.001**
NM12	20	0.760	18	0.457
NM13	20	-0.827	18	0.419
NF14	20	-1.891	18	0.075
NM15	20	-0.124	18	0.903
NM16	20	1.047	18	0.309
/u/				
NF1	20	0.302	18	0.766
NF2	20	1.449	18	0.164
NF3	20	1.525	18	0.145
NF4	20	0.602	18	0.554
NM5	18†	-0.687	16	0.502
NM6	---	---	---	---
NM7	20	-0.569	18	0.577
NF8	20	-1.277	18	0.218
NF9	20	0.737	18	0.470
NM10	20	0.572	18	0.575
NF11	20	3.930	18	<0.001**
NM12	20	0.261	18	0.797
NM13	20	-1.186	18	0.251
NF14	20	-0.737	18	0.470
NM15	20	-0.506	18	0.619
NM16	20	0.101	18	0.920
/o/				
NF1	30	-0.402	28	0.691
NF2	30	0.208	28	0.837
NF3	30	-1.955	28	0.061
NF4	30	-0.847	28	0.404
NM5	27†	-1.779	25	0.087
NM6	---	---	---	---
NM7	30	-0.998	28	0.327
NF8	30	-0.749	28	0.460
NF9	30	-0.187	28	0.853
NM10	30	2.601	28	0.015*
NF11	30	7.455	28	<0.001**
NM12	30	1.237	28	0.226
NM13	30	0.109	28	0.914
NF14	30	-1.027	28	0.313
NM15	30	-0.603	28	0.552
NM16	30	-0.595	28	0.557

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 7

Results of t tests on the "breath group cueing" effect for the connected speech data from individuals in the CP group – F2

Subject	N	t	df	p
/i/				
CPM1	20	-0.979	18	0.341
CPM2	20	-0.352	18	0.729
CPM3	20	-5.899	18	<0.001*
CPF4	20	0.514	18	0.613
/a/				
CPM1	20	-2.917	18	0.009*
CPM2	20	1.115	18	0.279
CPM3	20	-3.511	18	0.002**
CPF4	20	0.510	18	0.616
/u/				
CPM1	20	-1.939	18	0.068
CPM2	20	1.500	18	0.151
CPM3	20	1.381	18	0.184
CPF4	20	0.717	18	0.483
/ɔ/				
CPM1	30	0.516	28	0.610
CPM2	30	0.874	28	0.390
CPM3	30	0.0740	28	0.942
CPF4	30	-0.561	28	0.579

*Significant at 0.05 level
**Significant at 0.005 level

Appendix 8

Results of t tests on the "breath group cueing" effect for the connected speech data from individuals in the control group – F0

Subject	N	t	df	p
/i/				
NF1	20	2.990	18	0.008*
NF2	20	2.465	18	0.024*
NF3	20	2.623	18	0.017*
NF4	20	-1.700	18	0.106
NM5	18†	0.930	16	0.366
NM6	---	---	---	---
NM7	20	0.648	18	0.525
NF8	20	-0.798	18	0.435
NF9	20	0.251	18	0.805
NM10	20	0.286	18	0.778
NF11	20	15.760	18	<0.001**
NM12	20	-0.0492	18	0.961
NM13	20	0.0426	18	0.967
NF14	20	-1.812	18	0.087
NM15	20	0.122	18	0.904
NM16	20	-3.503	18	0.003**
/a/				
NF1	20	0.803	18	0.432
NF2	20	2.038	18	0.057
NF3	20	0.848	18	0.408
NF4	20	1.625	18	0.122
NM5	18†	0.994	16	0.335
NM6	---	---	---	---
NM7	20	0.383	18	0.706
NF8	20	0.889	18	0.386
NF9	20	0.785	18	0.443
NM10	20	2.828	18	0.011*
NF11	20	6.719	18	<0.001**
NM12	20	2.962	18	0.008**
NM13	20	8.232	18	<0.001**
NF14	20	0.971	18	0.344
NM15	20	3.054	18	0.007**
NM16	20	-0.946	18	0.357
/u/				
NF1	20	1.237	18	0.232
NF2	20	-2.164	18	0.044*
NF3	20	-3.627	18	0.002**
NF4	20	-0.226	18	0.823
NM5	18†	-1.311	16	0.209
NM6	---	---	---	---
NM7	20	0.246	18	0.808
NF8	20	0.933	18	0.363
NF9	20	1.222	18	0.238
NM10	20	0.753	18	0.461
NF11	20	4.702	18	<0.001**
NM12	20	-1.296	18	0.212
NM13	20	-0.141	18	0.890
NF14	20	-1.785	18	0.091
NM15	20	1.758	18	0.096
NM16	20	-1.884	18	0.076
/o/				
NF1	30	1.534	28	0.136
NF2	30	-0.145	28	0.886
NF3	30	-3.638	28	0.001**
NF4	30	-0.592	28	0.558
NM5	27†	-2.499	25	0.019*
NM6	---	---	---	---
NM7	30	1.031	28	0.312
NF8	30	0.692	28	0.495
NF9	30	-1.155	28	0.258
NM10	30	0.564	28	0.578
NF11	30	6.003	28	<0.001**
NM12	30	-0.307	28	0.761
NM13	30	-1.407	28	0.171
NF14	30	-2.809	28	0.009*
NM15	30	0.509	28	0.615
NM16	30	-1.189	28	0.245

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 9

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the CP group – F0

Subject	N	t	df	p
/i/				
CPM1	20	-4.473	18	< 0.001**
CPM2	20	-0.737	18	0.471
CPM3	20	-20.749	18	< 0.001**
CPF4	20	1.439	18	0.167
/a/				
CPM1	20	-2.917	18	0.009*
CPM2	20	0.518	18	0.610
CPM3	20	-17.569	18	< 0.001**
CPF4	20	1.622	18	0.122
/u/				
CPM1	20	-2.833	18	0.011*
CPM2	20	-1.958	18	0.066
CPM3	20	-11.275	18	< 0.001**
CPF4	20	-0.401	18	0.693
/ɔ/				
CPM1	30	-4.082	28	< 0.001**
CPM2	30	0.768	28	0.449
CPM3	30	-11.507	28	< 0.001**
CPF4	30	2.085	28	0.046*

*Significant at 0.05 level
**Significant at 0.005 level

Appendix 10

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the control group – %jitter

Subject	N	t	df	p
/i/				
NF1	20	0.676	18	0.508
NF2	20	1.070	18	0.299
NF3	20	-1.137	18	0.270
NF4	20	1.929	18	0.070
NM5	18†	-1.403	16	0.180
NM6	---	---	---	---
NM7	20	-3.093	18	0.006
NF8	20	-0.740	18	0.469
NF9	20	0.491	18	0.629
NM10	20	1.094	18	0.289
NF11	20	-0.280	18	0.783
NM12	20	1.640	18	0.118
NM13	20	0.744	18	0.466
NF14	20	1.345	18	0.195
NM15	20	1.646	18	0.117
NM16	20	0.967	18	0.346
/a/				
NF1	20	1.598	18	0.127
NF2	20	-1.258	18	0.224
NF3	20	-0.726	18	0.477
NF4	20	1.160	18	0.261
NM5	18†	1.768	16	0.096
NM6	---	---	---	---
NM7	20	1.549	18	0.139
NF8	20	-0.353	18	0.728
NF9	20	-0.914	18	0.373
NM10	20	1.819	18	0.086
NF11	20	-0.173	18	0.864
NM12	20	3.798	18	0.001**
NM13	20	4.210	18	<0.001**
NF14	20	0.783	18	0.444
NM15	20	2.186	18	0.042*
NM16	20	0.560	18	0.582
/u/				
NF1	20	-1.445	18	0.166
NF2	20	-0.555	18	0.585
NF3	20	0.836	18	0.414
NF4	20	-0.660	18	0.517
NM5	18†	0.550	16	0.590
NM6	---	---	---	---
NM7	20	-2.464	18	0.024*
NF8	20	0.902	18	0.379
NF9	20	-1.455	18	0.163
NM10	20	-2.099	18	0.050*
NF11	20	-3.515	18	0.002**
NM12	20	0.406	18	0.689
NM13	20	1.139	18	0.270
NF14	20	-1.142	18	0.269
NM15	20	0.844	18	0.410
NM16	20	-0.867	18	0.397
/o/				
NF1	30	-0.524	28	0.604
NF2	30	1.631	28	0.114
NF3	30	1.526	28	0.138
NF4	30	0.357	28	0.724
NM5	27†	2.853	25	0.009**
NM6	---	---	---	---
NM7	30	-1.279	28	0.211
NF8	30	0.685	28	0.499
NF9	30	1.553	28	0.132
NM10	30	1.946	28	0.062
NF11	30	0.692	28	0.495
NM12	30	0.0445	28	0.965
NM13	30	0.210	28	0.835
NF14	30	3.701	28	<0.001**
NM15	30	-0.106	28	0.916
NM16	30	-0.693	28	0.494

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 11

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the CP group – %jitter

Subject	N	t	df	p
/i/				
CPM1	20	2.527	18	0.021*
CPM2	20	-0.178	18	0.861
CPM3	20	-2.734	18	0.014*
CPF4	20	1.210	18	0.242
/a/				
CPM1	20	0.623	18	0.541
CPM2	20	-0.408	18	0.688
CPM3	20	-1.383	18	0.184
CPF4	20	0.544	18	0.593
/u/				
CPM1	20	1.285	18	0.215
CPM2	20	0.118	18	0.907
CPM3	20	-1.679	18	0.111
CPF4	20	0.529	18	0.603
/ɔ/				
CPM1	30	1.258	28	0.219
CPM2	30	0.777	28	0.444
CPM3	30	1.177	28	0.249
CPF4	30	2.303	28	0.029*

*Significant at 0.05 level

**Significant at 0.005 level

Appendix 12

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the control group – %shimmer

Subject	N	t	df	p
/i/				
NF1	20	0.905	18	0.377
NF2	20	-0.0327	18	0.974
NF3	20	-1.107	18	0.283
NF4	20	1.641	18	0.118
NM5	18†	0.147	16	0.885
NM6	---	---	---	---
NM7	20	-1.805	18	0.088
NF8	20	-0.662	18	0.516
NF9	20	0.119	18	0.906
NM10	20	-0.231	18	0.820
NF11	20	-1.368	18	0.188
NM12	20	0.456	18	0.654
NM13	20	-0.0528	18	0.958
NF14	20	0.943	18	0.358
NM15	20	0.547	18	0.591
NM16	20	-0.101	18	0.920
/a/				
NF1	20	1.456	18	0.163
NF2	20	-0.299	18	0.769
NF3	20	-2.822	18	0.011
NF4	20	-0.134	18	0.895
NM5	18†	2.087	16	0.053
NM6	---	---	---	---
NM7	20	1.394	18	0.180
NF8	20	2.334	18	0.031
NF9	20	1.700	18	0.106
NM10	20	1.504	18	0.150
NF11	20	2.895	18	0.010
NM12	20	3.088	18	0.006
NM13	20	-0.969	18	0.346
NF14	20	1.629	18	0.121
NM15	20	0.743	18	0.467
NM16	20	1.749	18	0.097
/u/				
NF1	20	-2.715	18	0.014
NF2	20	-1.283	18	0.216
NF3	20	-0.533	18	0.601
NF4	20	-1.175	18	0.255
NM5	18†	1.087	16	0.293
NM6	---	---	---	---
NM7	20	-1.625	18	0.122
NF8	20	-0.975	18	0.343
NF9	20	-1.102	18	0.285
NM10	20	-0.637	18	0.532
NF11	20	-2.568	18	0.019
NM12	20	0.684	18	0.503
NM13	20	1.313	18	0.206
NF14	20	-0.992	18	0.334
NM15	20	0.265	18	0.794
NM16	20	-0.710	18	0.487
/o/				
NF1	30	-0.605	28	0.550
NF2	30	2.228	28	0.034*
NF3	30	0.824	28	0.417
NF4	30	1.064	28	0.296
NM5	27†	2.019	25	0.054
NM6	---	---	---	---
NM7	30	-1.120	28	0.272
NF8	30	-0.507	28	0.616
NF9	30	2.036	28	0.051
NM10	30	1.172	28	0.251
NF11	30	1.337	28	0.192
NM12	30	2.199	28	0.036
NM13	30	-0.218	28	0.829
NF14	30	2.937	28	0. 007*
NM15	30	0.348	28	0.730
NM16	30	-0.771	28	0.447

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 13

Results of t tests on the "breath group cueing" effect for connected speech data from individuals in the CP group – %shimmer

Subject	N	t	df	p
/i/				
CPM1	20	2.723	18	0.014*
CPM2	20	-0.118	18	0.907
CPM3	20	-0.174	18	0.863
CPF4	20	1.150	18	0.265
/a/				
CPM1	20	-0.958	18	0.351
CPM2	20	-1.077	18	0.296
CPM3	20	1.474	18	0.158
CPF4	20	1.156	18	0.263
/u/				
CPM1	20	0.495	18	0.626
CPM2	20	1.252	18	0.227
CPM3	20	-1.260	18	0.224
CPF4	20	1.111	18	0.281
/ɔ/				
CPM1	30	1.313	28	0.200
CPM2	30	0.743	28	0.464
CPM3	30	1.319	28	0.198
CPF4	30	2.255	28	0.032*

*Significant at 0.05 level

**Significant at 0.005 level

Appendix 14

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the control group – SNR

Subject	N	t	df	p
/i/				
NF1	20	0.866	18	0.398
NF2	20	1.049	18	0.308
NF3	20	2.615	18	0.018*
NF4	20	-2.739	18	0.013*
NM5	18†	-1.113	16	0.282
NM6	---	---	---	---
NM7	20	2.269	18	0.036*
NF8	20	0.994	18	0.333
NF9	20	-0.445	18	0.661
NM10	20	0.503	18	0.621
NF11	20	0.750	18	0.463
NM12	20	-1.317	18	0.204
NM13	20	-0.114	18	0.910
NF14	20	-0.719	18	0.482
NM15	20	-1.574	18	0.133
NM16	20	-0.402	18	0.693
/a/				
NF1	20	-2.319	18	0.032
NF2	20	1.676	18	0.111
NF3	20	3.787	18	0.001**
NF4	20	0.279	18	0.783
NM5	18†	-1.113	16	0.282
NM6	---	---	---	---
NM7	20	-1.671	18	0.112
NF8	20	-1.470	18	0.159
NF9	20	0.00723	18	0.994
NM10	20	-3.436	18	0.003**
NF11	20	-1.093	18	0.289
NM12	20	-3.864	18	0.001**
NM13	20	-1.480	18	0.156
NF14	20	-1.098	18	0.287
NM15	20	-1.968	18	0.065
NM16	20	-0.789	18	0.441
/u/				
NF1	20	2.538	18	0.021*
NF2	20	-1.220	18	0.238
NF3	20	-1.520	18	0.146
NF4	20	0.000	18	1.000
NM5	18†	-2.454	16	0.026*
NM6	---	---	---	---
NM7	20	0.207	18	0.838
NF8	20	2.058	18	0.054
NF9	20	0.956	18	0.352
NM10	20	-1.080	18	0.294
NF11	20	2.603	18	0.018*
NM12	20	-0.987	18	0.337
NM13	20	-0.805	18	0.431
NF14	20	-1.137	18	0.270
NM15	20	-1.465	18	0.160
NM16	20	0.641	18	0.530
/ɔ/				
NF1	30	0.360	28	0.721
NF2	30	-1.396	28	0.174
NF3	30	-2.729	28	0.011*
NF4	30	-2.305	28	0.029*
NM5	27	-2.739	25	0.011*
NM6	---	---	---	---
NM7	30	1.307	28	0.202
NF8	30	1.070	28	0.294
NF9	30	-1.968	28	0.059
NM10	30	-2.907	28	0.007*
NF11	30	-1.081	28	0.289
NM12	30	-2.344	28	0.026*
NM13	30	-2.110	28	0.044*
NF14	30	-4.393	28	<0.001**
NM15	30	0.155	28	0.878
NM16	30	-1.145	28	0.262

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 15

Results of t tests on the “breath group cueing” effect for the connected speech data from individuals in the CP group – SNR

Subject	N	t	df	p
/i/				
CPM1	20	-2.389	18	0.028*
CPM2	20	0.893	18	0.384
CPM3	20	-1.285	18	0.215
CPF4	20	-0.966	18	0.347
/a/				
CPM1	20	-0.439	18	0.666
CPM2	20	0.114	18	0.910
CPM3	20	-1.447	18	0.165
CPF4	20	-0.471	18	0.643
/u/				
CPM1	20	0.581	18	0.568
CPM2	20	-0.672	18	0.510
CPM3	20	0.646	18	0.526
CPF4	20	-2.048	18	0.055
/ɔ/				
CPM1	30	-1.624	28	0.116
CPM2	30	-0.653	28	0.519
CPM3	30	-1.744	28	0.092
CPF4	30	-3.856	28	<0.001**

*Significant at 0.05 level

**Significant at 0.005 level

Appendix 16

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – VOT

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 12.31, p < 0.001**	F (4, 60) = 4.443, p = 0.003**	F (8, 60) = 0.744, p = 0.653
NM13	75	F (2, 60) = 76.26, p < 0.001**	F (4, 60) = 1.761, p = 0.149	F (8, 60) = 3.060, p = 0.006*
NM15	75	F (2, 60) = 3.095, p = 0.053	F (4, 60) = 1.092, p = 0.369	F (8, 60) = 0.856, p = 0.558
NM16	75	F (2, 60) = 103.2, p < 0.001**	F (4, 60) = 0.960, p = 0.436	F (8, 60) = 0.357, p = 0.939
CPM1	75	F (2, 60) = 13.37, p < 0.001**	F (4, 60) = 2.485, p = 0.053	F (8, 60) = 1.179, p = 0.327
CPM2	75	F (2, 60) = 12.31, p < 0.001**	F (4, 60) = 4.443, p = 0.003**	F (8, 60) = 0.744, p = 0.653
CPM3	75	F (2, 60) = 19.33, p < 0.001**	F (4, 60) = 4.124, p = 0.005**	F (8, 60) = 1.142, p = 0.349
CPF4	73†	F (2, 58) = 3.265, p = 0.045*	F (4, 58) = 0.905, p = 0.467	F (8, 58) = 1.365, p = 0.231
/a/				
NF2	73†	F (2, 58) = 13.155, p < 0.001**	F (4, 58) = 4.493, p = 0.003**	F (8, 58) = 0.609, p = 0.766
NM13	75	F (2, 60) = 44.031, p < 0.001**	F (4, 60) = 4.672, p = 0.002**	F (8, 60) = 1.535, p = 0.164
NM15	75	F (2, 60) = 0.8490, p = 0.433	F (4, 60) = 5.104, p = 0.001**	F (8, 60) = 1.006, p = 0.441
NM16	75	F (2, 60) = 32.398, p < 0.001**	F (4, 60) = 0.087, p = 0.986	F (8, 60) = 0.685, p = 0.703
CPM1	74†	F (2, 59) = 37.893, p < 0.001**	F (4, 59) = 0.836, p = 0.508	F (8, 59) = 3.184, p = 0.005**
CPM2	73†	F (2, 58) = 13.155, p < 0.001**	F (4, 58) = 4.493, p = 0.003**	F (8, 58) = 0.609, p = 0.766
CPM3	75	F (2, 60) = 14.945, p < 0.001**	F (4, 60) = 9.526, p < 0.001**	F (8, 60) = 1.791, p = 0.097
CPF4	75	F (2, 60) = 1.6820, p = 0.195	F (4, 60) = 3.131, p = 0.021*	F (8, 60) = 0.259, p = 0.976
/u/				
NF2	75	F (2, 60) = 2.342, p = 0.105	F (4, 58) = 0.926, p = 0.455	F (8, 58) = 0.466, p = 0.875
NM13	75	F (2, 60) = 26.48, p < 0.001**	F (4, 60) = 3.380, p = 0.015*	F (8, 60) = 1.223, p = 0.302
NM15	75	F (2, 60) = 4.904, p = 0.011*	F (4, 60) = 5.263, p = 0.001**	F (8, 60) = 0.905, p = 0.519
NM16	75	F (2, 60) = 83.55, p < 0.001**	F (4, 60) = 2.217, p = 0.078*	F (8, 60) = 0.741, p = 0.655
CPM1	75	F (2, 60) = 5.146, p = 0.009*	F (4, 60) = 2.201, p = 0.080	F (8, 60) = 0.819, p = 0.589
CPM2	75	F (2, 60) = 2.342, p = 0.105	F (4, 60) = 0.926, p = 0.455	F (8, 60) = 0.466, p = 0.875
CPM3	75	F (2, 60) = 12.38, p < 0.001**	F (4, 60) = 8.314, p < 0.001**	F (8, 60) = 1.625, p = 0.137
CPF4	75	F (2, 60) = 3.361, p = 0.032*	F (4, 60) = 5.253, p = 0.001**	F (8, 60) = 1.085, p = 0.386
/ɔ/				
NF2	75	F (2, 60) = 2.863, p = 0.065	F (4, 60) = 5.327, p < 0.001**	F (8, 60) = 0.673, p = 0.713
NM13	75	F (2, 60) = 11.35, p < 0.001**	F (4, 60) = 8.339, p < 0.001**	F (8, 60) = 0.379, p = 0.928
NM15	75	F (2, 60) = 1.501, p = 0.231	F (4, 60) = 1.225, p = 0.310	F (8, 60) = 1.170, p = 0.332
NM16	75	F (2, 60) = 36.08, p < 0.001**	F (4, 60) = 0.765, p = 0.552	F (8, 60) = 0.303, p = 0.962
CPM1	75	F (2, 60) = 16.18, p < 0.001**	F (4, 60) = 1.351, p = 0.262	F (8, 60) = 1.731, p = 0.110
CPM2	75	F (2, 60) = 2.863, p = 0.065	F (4, 60) = 5.327, p < 0.001**	F (8, 60) = 0.673, p = 0.713
CPM3	75	F (2, 60) = 1.281, p = 0.285	F (4, 60) = 8.717, p < 0.001**	F (8, 60) = 0.719, p = 0.674
CPF4	74†	F (2, 59) = 1.307, p = 0.278	F (4, 59) = 1.205, p = 0.318	F (8, 59) = 0.451, p = 0.885

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 17

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – vowel duration

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 0.166, p = 0.847	F (4, 60) = 1.294, p = 0.282	F (8, 60) = 0.736, p = 0.660
NM13	75	F (2, 60) = 4.201, p = 0.020*	F (4, 60) = 19.83, p < 0.001**	F (8, 60) = 0.419, p = 0.905
NM15	75	F (2, 60) = 0.817, p = 0.446	F (4, 60) = 1.871, p = 0.127	F (8, 60) = 1.540, p = 0.163
NM16	75	F (2, 60) = 20.49, p = 0.015*	F (4, 60) = 20.49, p < 0.001**	F (8, 60) = 1.366, p = 0.230
CPM1	75	F (2, 60) = 2.281, p = 0.111	F (4, 60) = 13.43, p < 0.001**	F (8, 60) = 1.255, p = 0.284
CPM2	75	F (2, 60) = 0.166, p = 0.847	F (4, 60) = 1.294, p = 0.282	F (8, 60) = 0.736, p = 0.660
CPM3	75	F (2, 60) = 4.578, p = 0.014*	F (4, 60) = 2.639, p = 0.042*	F (8, 60) = 2.034, p = 0.057
CPF4	72†	F (2, 57) = 0.920, p = 0.404	F (4, 57) = 0.956, p = 0.439	F (8, 57) = 0.936, p = 0.495
/a/				
NF2	73†	F (2, 58) = 0.525, p = 0.595	F (4, 58) = 2.362, p = 0.064	F (8, 58) = 0.407, p = 0.912
NM13	75	F (2, 60) = 0.103, p = 0.902	F (4, 60) = 45.80, p < 0.001**	F (8, 60) = 0.095, p = 0.999
NM15	75	F (2, 60) = 2.413, p = 0.098	F (4, 60) = 3.751, p = 0.009**	F (8, 60) = 1.255, p = 0.284
NM16	75	F (2, 60) = 0.674, p = 0.514	F (4, 60) = 10.27, p < 0.001**	F (8, 60) = 0.545, p = 0.818
CPM1	74†	F (2, 59) = 20.82, p < 0.001**	F (4, 59) = 18.11, p < 0.001**	F (8, 59) = 4.760, p < 0.001**
CPM2	73†	F (2, 58) = 0.525, p = 0.595	F (4, 58) = 2.362, p = 0.064	F (8, 58) = 0.470, p = 0.912
CPM3	75	F (2, 60) = 0.074, p = 0.929	F (4, 60) = 1.801, p = 0.140	F (8, 60) = 0.941, p = 0.491
CPF4	75	F (2, 60) = 0.661, p = 0.520	F (4, 60) = 60.70, p < 0.001**	F (8, 60) = 1.044, p = 0.414
/u/				
NF2	75	F (2, 60) = 5.494, p = 0.006*	F (4, 60) = 3.405, p = 0.014*	F (8, 60) = 0.529, p = 0.830
NM13	75	F (2, 60) = 0.566, p = 0.571	F (4, 60) = 24.89, p < 0.001**	F (8, 60) = 0.188, p = 0.992
NM15	75	F (2, 60) = 0.580, p = 0.563	F (4, 60) = 2.217, p = 0.078	F (8, 60) = 1.021, p = 0.430
NM16	75	F (2, 60) = 0.515, p = 0.600	F (4, 60) = 14.60, p < 0.001**	F (8, 60) = 0.680, p = 0.707
CPM1	74†	F (2, 60) = 2.327, p = 0.106	F (4, 60) = 9.221, p < 0.001**	F (8, 60) = 0.879, p = 0.540
CPM2	75	F (2, 60) = 5.494, p = 0.006*	F (4, 60) = 3.405, p = 0.014*	F (8, 60) = 0.529, p = 0.830
CPM3	75	F (2, 60) = 1.009, p = 0.371	F (4, 60) = 1.463, p = 0.225	F (8, 60) = 1.813, p = 0.092
CPF4	75	F (2, 60) = 0.224, p = 0.800	F (4, 60) = 48.77, p < 0.001**	F (8, 60) = 1.316, p = 0.253
/ɔ/				
NF2	75	F (2, 60) = 0.550, p = 0.580	F (4, 60) = 0.937, p = 0.449	F (8, 60) = 0.886, p = 0.534
NM13	75	F (2, 60) = 0.596, p = 0.554	F (4, 60) = 53.16, p < 0.001**	F (8, 60) = 0.823, p = 0.585
NM15	75	F (2, 60) = 1.937, p = 0.153	F (4, 60) = 4.429, p = 0.003**	F (8, 60) = 0.846, p = 0.567
NM16	75	F (2, 60) = 2.059, p = 0.137	F (4, 60) = 13.35, p < 0.001**	F (8, 60) = 0.994, p = 0.450
CPM1	75	F (2, 60) = 3.340, p = 0.042	F (4, 60) = 14.65, p < 0.001**	F (8, 60) = 0.815, p = 0.593
CPM2	75	F (2, 60) = 0.550, p = 0.580	F (4, 60) = 0.937, p = 0.449	F (8, 60) = 0.886, p = 0.534
CPM3	75	F (2, 60) = 0.998, p = 0.375	F (4, 60) = 1.048, p = 0.390	F (8, 60) = 1.193, p = 0.319
CPF4	72†	F (2, 59) = 0.108, p = 0.898	F (4, 59) = 23.38, p < 0.001**	F (8, 59) = 1.803, p = 0.095

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 18

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – F1

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 2.148, p = 0.126	F (4, 60) = 1.456, p = 0.227	F (8, 60) = 0.611, p = 0.765
NM13	75	F (2, 60) = 0.691, p = 0.505	F (4, 60) = 1.101, p = 0.365	F (8, 60) = 1.027, p = 0.426
NM15	75	F (2, 60) = 5.366, p = 0.007*	F (4, 60) = 7.048, p < 0.001**	F (8, 60) = 0.992, p = 0.451
NM16	75	F (2, 60) = 0.978, p = 0.382	F (4, 60) = 0.979, p = 0.426	F (8, 60) = 0.943, p = 0.486
CPM1	75	F (2, 60) = 2.747, p < 0.001**	F (4, 60) = 1.438, p = 0.232	F (8, 60) = 1.461, p = 0.191
CPM2	75	F (2, 60) = 2.148, p = 0.126	F (4, 60) = 1.456, p = 0.227	F (8, 60) = 0.611, p = 0.765
CPM3	75	F (2, 60) = 1.557, p = 0.219	F (4, 60) = 40.07, p < 0.001**	F (8, 60) = 2.724, p = 0.012*
CPF4	72†	F (2, 57) = 1.451, p = 0.243	F (4, 57) = 0.818, p = 0.519	F (8, 57) = 1.682, p = 0.123
/a/				
NF2	73†	F (2, 58) = 0.591, p = 0.557	F (4, 58) = 0.921, p = 0.458	F (8, 58) = 1.045, p = 0.414
NM13	75	F (2, 60) = 3.976, p = 0.024*	F (4, 60) = 3.385, p = 0.015*	F (8, 60) = 1.133, p = 0.355
NM15	75	F (2, 60) = 4.414, p = 0.016*	F (4, 60) = 1.384, p = 0.250	F (8, 60) = 1.842, p = 0.087
NM16	75	F (2, 60) = 2.174, p = 0.123	F (4, 60) = 0.348, p = 0.844	F (8, 60) = 1.070, p = 0.396
CPM1	74†	F (2, 59) = 31.78, p < 0.001**	F (4, 59) = 4.304, p = 0.004**	F (8, 59) = 1.136, p = 0.353
CPM2	73†	F (2, 58) = 0.591, p = 0.557	F (4, 58) = 0.921, p = 0.458	F (8, 58) = 1.045, p = 0.414
CPM3	75	F (2, 60) = 4.881, p = 0.011*	F (4, 60) = 16.17, p < 0.001**	F (8, 60) = 1.239, p = 0.292
CPF4	75	F (2, 60) = 0.929, p = 0.401	F (4, 60) = 2.354, p = 0.064	F (8, 60) = 2.126, p = 0.047
/u/				
NF2	75	F (2, 60) = 1.702, p = 0.191	F (4, 60) =10.19, p < 0.001**	F (8, 60) = 0.617, p = 0.760
NM13	75	F (2, 60) = 0.661, p = 0.520	F (4, 60) =6.181, p < 0.001**	F (8, 60) = 0.699, p = 0.691
NM15	75	F (2, 60) = 1.014, p = 0.369	F (4, 60) = 0.749, p = 0.563	F (8, 60) = 0.951, p = 0.482
NM16	75	F (2, 60) = 0.090, p = 0.914	F (4, 60) = 2.560, p = 0.048*	F (8, 60) = 0.460, p = 0.879
CPM1	75	F (2, 60) = 9.434, p < 0.001**	F (4, 60) = 2.218, p = 0.088	F (8, 60) = 0.412, p = 0.909
CPM2	75	F (2, 60) = 1.702, p = 0.191	F (4, 60) = 10.19, p < 0.001**	F (8, 60) = 0.617, p = 0.760
CPM3	75	F (2, 60) = 0.834, p = 0.439	F (4, 60) = 7.704, p < 0.001**	F (8, 60) = 1.066, p = 0.399
CPF4	75	F (2, 60) = 0.035, p = 0.965	F (4, 60) = 0.317, p = 0.866	F (8, 60) = 1.460, p = 0.191
/ɔ/				
NF2	75	F (2, 60) = 30.91, p = 0.407	F (4, 60) = 1.030, p = 0.4	F (8, 60) = 1.199, p = 0.315
NM13	75	F (2, 60) = 4.740, p = 0.012*	F (4, 60) = 7.742, p < 0.001**	F (8, 60) = 1.227, p = 0.299
NM15	75	F (2, 60) = 5.900, p = 0.005**	F (4, 60) = 3.052, p = 0.023*	F (8, 60) = 0.928, p = 0.500
NM16	75	F (2, 60) = 1.135, p = 0.328	F (4, 60) = 0.494, p = 0.740	F (8, 60) = 0.792, p = 0.612
CPM1	75	F (2, 60) = 34.16, p < 0.001**	F (4, 60) = 3.445, p = 0.013	F (8, 60) = 1.136, p = 0.353
CPM2	75	F (2, 60) = 0.913, p = 0.407	F (4, 60) = 1.030, p = 0.400	F (8, 60) = 1.199, p = 0.315
CPM3	75	F (2, 60) = 1.006, p = 0.372	F (4, 60) = 1.018, p = 0.405	F (8, 60) = 1.005, p = 0.442
CPF4	73†	F (2, 59) = 1.472, p = 0.238	F (4, 59) = 1.092, p = 0.369	F (8, 59) = 0.772, p = 0.629

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 19

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – F2

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 1.221, p = 0.302	F (4, 60) = 2.556, p = 0.048*	F (8, 60) = 1.190, p = 0.318
NM13	75	F (2, 60) = 0.106, p = 0.899	F (4, 60) = 0.416, p = 0.797	F (8, 60) = 0.425, p = 0.901
NM15	75	F (2, 60) = 2.762, p = 0.071	F (4, 60) = 1.253, p = 0.298	F (8, 60) = 0.304, p = 0.962
NM16	75	F (2, 60) = 1.976, p = 0.148	F (4, 60) = 2.515, p = 0.051	F (8, 60) = 0.495, p = 0.855
CPM1	75	F (2, 60) = 11.64, p < 0.001**	F (4, 60) = 1.546, p = 0.201	F (8, 60) = 0.990, p = 0.453
CPM2	75	F (2, 60) = 1.221, p = 0.302	F (4, 60) = 2.556, p = 0.048*	F (8, 60) = 1.194, p = 0.318
CPM3	75	F (2, 60) = 20.33, p < 0.001**	F (4, 60) = 55.12, p < 0.001**	F (8, 60) = 5.403, p < 0.001**
CPF4	72†	F (2, 57) = 22.26, p < 0.001**	F (4, 57) = 3.008, p = 0.025*	F (8, 57) = 2.704, p = 0.014*
/a/				
NF2	73†	F (2, 58) = 14.59, p < 0.001**	F (4, 58) = 0.944, p = 0.445	F (8, 58) = 1.015, p = 0.435
NM13	75	F (2, 60) = 8.194, p < 0.001**	F (4, 60) = 1.188, p = 0.325	F (8, 60) = 1.919, p = 0.073
NM15	75	F (2, 60) = 18.65, p < 0.001**	F (4, 60) = 1.356, p = 0.260	F (8, 60) = 0.779, p = 0.623
NM16	75	F (2, 60) = 42.62, p < 0.001**	F (4, 60) = 0.516, p = 0.724	F (8, 60) = 0.956, p = 0.479
CPM1	74†	F (2, 59) = 2.283, p = 0.111	F (4, 59) = 0.303, p = 0.875	F (8, 59) = 0.991, p = 0.452
CPM2	73†	F (2, 58) = 14.59, p < 0.001**	F (4, 58) = 0.944, p = 0.445	F (8, 59) = 1.015, p = 0.435
CPM3	75	F (2, 60) = 25.91, p < 0.001**	F (4, 60) = 11.23, p < 0.001**	F (8, 60) = 1.797, p = 0.095
CPF4	75	F (2, 60) = 1.587, p = 0.213	F (4, 60) = 1.605, p = 0.185	F (8, 60) = 2.242, p = 0.036*
/u/				
NF2	75	F (2, 60) = 2.852, p = 0.066	F (4, 60) = 3.255, p = 0.018*	F (8, 60) = 0.676, p = 0.711
NM13	75	F (2, 60) = 0.058, p = 0.944	F (4, 60) = 11.65, p < 0.001**	F (8, 60) = 1.685, p = 0.121
NM15	75	F (2, 60) = 78.62, p < 0.001**	F (4, 60) = 1.686, p = 0.165	F (8, 60) = 0.454, p = 0.883
NM16	75	F (2, 60) = 54.75, p < 0.001**	F (4, 60) = 0.947, p = 0.443	F (8, 60) = 0.691, p = 0.698
CPM1	75	F (2, 60) = 32.11, p < 0.001**	F (4, 60) = 4.052, p = 0.006*	F (8, 60) = 1.851, p = 0.085
CPM2	75	F (2, 60) = 2.852, p = 0.066	F (4, 60) = 3.255, p = 0.018*	F (8, 60) = 0.676, p = 0.711
CPM3	75	F (2, 60) = 24.44, p < 0.001**	F (4, 60) = 22.42, p < 0.001**	F (8, 60) = 0.637, p = 0.744
CPF4	75	F (2, 60) = 11.43, p < 0.001**	F (4, 60) = 3.417, p = 0.014*	F (8, 60) = 0.524, p = 0.834
/ɔ/				
NF2	75	F (2, 60) = 1.153, p = 0.322	F (4, 60) = 1.497, p = 0.214	F (8, 60) = 0.217, p = 0.987
NM13	75	F (2, 60) = 0.992, p = 0.377	F (4, 60) = 1.066, p = 0.381	F (8, 60) = 0.977, p = 0.462
NM15	75	F (2, 60) = 1.100, p = 0.339	F (4, 60) = 1.671, p = 0.169	F (8, 60) = 0.630, p = 0.750
NM16	75	F (2, 60) = 5.272, p = 0.008*	F (4, 60) = 3.235, p = 0.018*	F (8, 60) = 0.330, p = 0.951
CPM1	75	F (2, 60) = 6.924, p = 0.002**	F (4, 60) = 0.797, p = 0.551	F (8, 60) = 1.134, p = 0.354
CPM2	75	F (2, 60) = 1.153, p = 0.322	F (4, 60) = 1.497, p = 0.214	F (8, 60) = 0.217, p = 0.987
CPM3	75	F (2, 60) = 13.22, p < 0.001**	F (4, 60) = 6.583, p < 0.001**	F (8, 60) = 1.253, p = 0.285
CPF4	73†	F (2, 58) = 12.27, p < 0.001**	F (4, 58) = 3.705, p = 0.009*	F (8, 58) = 4.310, p < 0.001**

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 20

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – F0

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 9.510, p < 0.001**	F (4, 60) = 4.537, p = 0.003**	F (8, 60) = 1.205, p = 0.312
NM13	75	F (2, 60) = 0.161, p = 0.852	F (4, 60) = 0.519, p = 0.722	F (8, 60) = 0.330, p = 0.951
NM15	75	F (2, 60) = 0.872, p = 0.423	F (4, 60) = 16.06, p < 0.001**	F (8, 60) = 0.497, p = 0.854
NM16	75	F (2, 60) = 1.595, p = 0.211	F (4, 60) = 11.43, p < 0.001**	F (8, 60) = 0.203, p = 0.989
CPM1	75	F (2, 60) = 1.098, p = 0.34	F (4, 60) = 1.107, p = 0.362	F (8, 60) = 1.002, p = 0.444
CPM2	75	F (2, 60) = 9.510, p < 0.001**	F (4, 60) = 4.537, p = 0.003**	F (8, 60) = 1.205, p = 0.312
CPM3	75	F (2, 60) = 1.772, p = 0.179	F (4, 60) = 21.97, p < 0.001**	F (8, 60) = 0.295, p = 0.965
CPF4	72†	F (2, 57) = 0.988, p = 0.379	F (4, 57) = 9.096, p < 0.001**	F (8, 57) = 1.785, p = 0.099
/a/				
NF2	73†	F (2, 58) = 0.049, p = 0.952	F (4, 58) = 9.350, p < 0.001**	F (8,58) = 1.015, p = 0.435
NM13	75	F (2, 60) = 0.056, p = 0.946	F (4, 60) = 0.750, p = 0.562	F (8, 60) = 0.205, p = 0.989
NM15	75	F (2, 60) = 0.051, p = 0.950	F (4, 60) = 6.351, p < 0.001**	F (8, 60) = 0.279, p = 0.971
NM16	75	F (2, 60) = 0.868, p = 0.425	F (4, 60) = 7.797, p < 0.001**	F (8, 60) = 7.580, p = 0.641
CPM1	74†	F (2, 59) = 0.984, p = 0.380	F (4, 59) = 0.473, p = 0.756	F (8, 59) = 1.061, p = 0.402
CPM2	73†	F (2, 58) = 0.049, p = 0.952	F (4, 58) = 9.935, p < 0.001**	F (8, 58) = 1.015, p = 0.435
CPM3	75	F (2, 60) = 1.658, p = 0.199	F (4, 60) = 32.21, p < 0.001**	F (8, 60) = 0.501, p = 0.851
CPF4	75	F (2, 60) = 1.781, p = 0.177	F (4, 60) = 1.057, p = 0.386	F (8, 60) = 1.534 p = 0.165
/u/				
NF2	75	F (2, 60) = 2.407, p = 0.099	F (4, 60) = 13.53, p < 0.001**	F (8, 60) = 1.177, p = 0.328
NM13	75	F (2, 60) = 0.724, p = 0.489	F (4, 60) = 2.051, p = 0.09	F (8, 60) = 0.177, p = 0.993
NM15	75	F (2, 60) = 1.042, p = 0.359	F (4, 60) = 11.30, p < 0.001**	F (8, 60) = 0.411, p = 0.910
NM16	75	F (2, 60) = 0.959, p = 0.389	F (4, 60) = 14.61, p < 0.001**	F (8, 60) = 0.786, p = 0.617
CPM1	75	F (2, 60) = 0.391, p = 0.678	F (4, 60) = 2.577, p = 0.046*	F (8, 60) = 0.894, p = 0.527
CPM2	75	F (2, 60) = 2.407, p = 0.099	F (4, 60) = 13.53, p < 0.001**	F (8, 60) = 1.177, p = 0.328
CPM3	75	F (2, 60) = 0.699, p = 0.501	F (4, 60) = 0.819, p = 0.518	F (8, 60) = 1.067, p = 0.398
CPF4	75	F (2, 60) = 4.419, p = 0.016	F (4, 60) = 1.487, p = 0.217	F (8, 60) = 0.829, p = 0.581
/ɔ/				
NF2	75	F (2, 60) = 2.377, p = 0.102	F (4, 60) = 2.751, p = 0.036*	F (8, 60) = 0.505, p = 0.848
NM13	75	F (2, 60) = 1.013, p = 0.369	F (4, 60) = 1.133, p = 0.350	F (8, 60) = 1.803, p = 0.094
NM15	75	F (2, 60) = 0.753, p = 0.475	F (4, 60) = 5.965, p < 0.001**	F (8, 60) = 0.792, p = 0.611
NM16	75	F (2, 60) = 0.013, p = 0.987	F (4, 60) = 10.02, p < 0.001**	F (8, 60) = 0.309, p = 0.960
CPM1	75	F (2, 60) = 0.524, p = 0.595	F (4, 60) = 0.592, p = 0.670	F (8, 60) = 1.117, p = 0.365
CPM2	75	F (2, 60) = 2.377, p = 0.102	F (4, 60) = 2.751, p = 0.036*	F (8, 60) = 0.505, p = 0.848
CPM3	75	F (2, 60) = 1.113, p = 0.335	F (4, 60) = 26.08, p < 0.001**	F (8, 60) = 0.426, p = 0.901
CPF4	73†	F (2, 58) = 4.286, p = 0.018*	F (4, 58) = 3.089, p = 0.023*	F (8, 58) = 2.012, p = 0.061

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 21

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – %jitter

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/**i**/				
NF2	75	F (2, 60) = 2.230, p = 0.116	F (4, 60) = 1.551, p = 0.199	F (8, 60) = 0.824, p = 0.585
NM13	75	F (2, 60) = 0.402, p = 0.671	F (4, 60) = 1.987, p = 0.108	F (8, 60) = 1.949, p = 0.069
NM15	75	F (2, 60) = 4.161, p = 0.020*	F (4, 60) = 10.22, p < 0.001**	F (8, 60) = 0.595, p = 0.778
NM16	75	F (2, 60) = 2.722, p = 0.074	F (4, 60) = 32.17, p < 0.001**	F (8, 60) = 0.488, p = 0.860
CPM1	75	F (2, 60) = 0.362, p = 0.698	F (4, 60) = 1.196, p = 0.322	F (8, 60) = 0.838, p = 0.573
CPM2	75	F (2, 60) = 2.230, p = 0.116	F (4, 60) = 1.551, p = 0.199	F (8, 60) = 0.824, p = 0.585
CPM3	75	F (2, 60) = 1.018, p = 0.367	F (4, 60) = 34.24, p < 0.001**	F (8, 60) = 0.396, p = 0.918
CPF4	72†	F (2, 57) = 1.077, p = 0.348	F (4, 57) = 5.100, p < 0.001**	F (8, 57) = 2.381, p = 0.027*
/**a**/				
NF2	73†	F (2, 58) = 0.128, p = 0.880	F (4, 58) = 2.371, p = 0.063	F (8, 58) = 0.826, p = 0.567
NM13	75	F (2, 60) = 1.155, p = 0.322	F (4, 60) = 1.015, p = 0.407	F (8, 60) = 1.082, p = 0.388
NM15	75	F (2, 60) = 0.512, p = 0.600	F (4, 60) = 1.963, p = 0.112	F (8, 60) = 0.950, p = 0.483
NM16	75	F (2, 60) = 0.512, p = 0.602	F (4, 60) = 19.59, p < 0.001**	F (8, 60) = 1.725, p = 0.111
CPM1	74†	F (2, 59) = 1.166, p = 0.319	F (4, 59) = 0.843, p = 0.504	F (8, 59) = 1.125, p = 0.360
CPM2	73†	F (2, 58) = 0.128, p = 0.880	F (4, 58) = 2.371, p = 0.063	F (8, 58) = 0.846, p = 0.567
CPM3	75	F (2, 60) = 0.933, p = 0.399	F (4, 60) = 20.69, p < 0.001**	F (8, 60) = 1.978, p = 0.065
CPF4	75	F (2, 60) = 0.626, p = 0.538	F (4, 60) = 4.779, p = 0.002**	F (8, 60) = 0.366, p = 0.934
/**u**/				
NF2	75	F (2, 60) = 2.268, p = 0.112	F (4, 60) = 3.850, p = 0.008*	F (8, 60) = 0.866, p = 0.055
NM13	75	F (2, 60) = 0.779, p = 0.464	F (4, 60) = 8.025, p < 0.001**	F (8, 60) = 0.659, p = 0.725
NM15	75	F (2, 60) = 1.509, p = 0.229	F (4, 60) = 4.905, p = 0.002**	F (8, 60) = 0.820, p = 0.588
NM16	75	F (2, 60) = 1.368, p = 0.262	F (4, 60) = 25.77, p < 0.001**	F (8, 60) = 0.790, p = 0.613
CPM1	75	F (2, 60) = 0.638, p = 0.532	F (4, 60) = 0.749, p = 0.562	F (8, 60) = 0.970, p = 0.468
CPM2	75	F (2, 60) = 2.268, p = 0.112	F (4, 60) = 3.850, p = 0.008*	F (8, 60) = 0.866, p = 0.550
CPM3	75	F (2, 60) = 3.647, p = 0.032*	F (4, 60) = 26.14, p < 0.001**	F (8, 60) = 1.351, p = 0.237
CPF4	75	F (2, 60) = 0.332, p = 0.719	F (4, 60) = 3.116, p = 0.021*	F (8, 60) = 0.659, p = 0.725
/ɔ/				
NF2	75	F (2, 60) = 0.721, p = 0.490	F (4, 60) = 2.190, p = 0.081	F (8, 60) = 1.091, p = 0.382
NM13	75	F (2, 60) = 0.428, p = 0.654	F (4, 60) = 8.749, p < 0.001**	F (8, 60) = 0.877, p = 0.541
NM15	75	F (2, 60) = 0.643, p = 0.529	F (4, 60) = 4.697, p = 0.002**	F (8, 60) = 0.648, p = 0.734
NM16	75	F (2, 60) = 2.430, p = 0.097	F (4, 60) = 47.05, p < 0.001**	F (8, 60) = 0.935, p = 0.495
CPM1	75	F (2, 60) = 0.577, p = 0.564	F (4, 60) = 1.148, p = 0.343	F (8, 60) = 1.408, p = 0.212
CPM2	75	F (2, 60) = 0.721, p = 0.490	F (4, 60) = 2.190, p = 0.081	F (8, 60) = 1.091, p = 0.382
CPM3	75	F (2, 60) = 2.007, p = 0.143	F (4, 60) = 37.82, p < 0.001**	F (8, 60) = 1.219, p = 0.304
CPF4	73†	F (2, 58) = 2.672, p = 0.078	F (4, 58) = 4.776, p = 0.002**	F (8, 58) = 1.443, p = 0.198

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 22

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – %shimmer

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 1.450, p = 0.244	F (4, 60) = 1.430, p = 0.235	F (8, 60) = 1.403, p = 0.214
NM13	75	F (2, 60) = 0.625, p = 0.539	F (4, 60) = 5.044, p = 0.001**	F (8, 60) = 1.024, p = 0.428
NM15	75	F (2, 60) = 1.185, p = 0.313	F (4, 60) = 1.413, p = 0.241	F (8, 60) = 1.379, p = 0.224
NM16	75	F (2, 60) = 0.180, p = 0.836	F (4, 60) = 5.079, p = 0.001**	F (8, 60) = 11.32, p = 0.252
CPM1	75	F (2, 60) = 0.359, p = 0.700	F (4, 60) = 0.677, p = 0.610	F (8, 60) = 0.728, p = 0.667
CPM2	75	F (2, 60) = 1.445, p = 0.244	F (4, 60) = 1.430, p = 0.214	F (8, 60) = 1.403, p = 0.214
CPM3	75	F (2, 60) = 3.901, p = 0.026*	F (4, 60) = 13.59, p < 0.001**	F (8, 60) = 0.906, p = 0.518
CPF4	72†	F (2, 57) = 0.075, p = 0.928	F (4, 57) = 7.799, p < 0.001**	F (8, 57) = 1.420, p = 0.208
/a/				
NF2	73†	F (2, 58) = 1.065, p = 0.351	F (4, 58) = 7.175, p < 0.001**	F (8, 58) = 1.676, p = 0.124
NM13	75	F (2, 60) = 6.333, p = 0.003**	F (4, 60) = 4.309, p = 0.004**	F (8, 60) = 1.759, p = 0.103
NM15	75	F (2, 60) = 0.618, p = 0.542	F (4, 60) = 5.083, p = 0.001**	F (8, 60) = 0.896, p = 0.526
NM16	75	F (2, 60) = 0.540, p = 0.586	F (4, 60) = 2.700, p = 0.039*	F (8, 60) = 3.586, p = 0.002 **
CPM1	74†	F (2, 59) = 3.102, p = 0.052	F (4, 59) = 1.005, p = 0.107	F (8, 59) = 1.333, p = 0.245
CPM2	73†	F (2, 58) = 1.065, p = 0.351	F (4, 58) = 7.175, p < 0.001**	F (8, 58) = 1.676, p = 0.124
CPM3	75	F (2, 60) = 0.801, p = 0.454	F (4, 60) = 6.907, p < 0.001**	F (8, 60) = 0.756, p = 0.642
CPF4	75	F (2, 60) = 0.285, p = 0.753	F (4, 60) = 5.219, p < 0.001**	F (8, 60) = 0.191, p = 0.991
/u/				
NF2	75	F (2, 60) = 1.906, p = 0.158	F (4, 60) = 3.252, p = 0.018*	F (8, 60) = 0.910, p = 0.514
NM13	75	F (2, 60) = 1.751, p = 0.182	F (4, 60) = 3.381, p = 0.015*	F (8, 60) = 0.534, p = 0.826
NM15	75	F (2, 60) = 1.636, p = 0.203	F (4, 60) = 3.747, p = 0.009*	F (8, 60) = 0.614, p = 0.724
NM16	75	F (2, 60) = 0.164, p = 0.849	F (4, 60) = 10.35, p < 0.001**	F (8, 60) = 1.625, p = 0.137
CPM1	75	F (2, 60) = 1.332, p = 0.272	F (4, 60) = 1.130, p = 0.351	F (8, 60) = 0.877, p = 0.541
CPM2	75	F (2, 60) = 1.906, p = 0.158	F (4, 60) = 3.252, p = 0.018*	F (8, 60) = 0.910, p = 0.514
CPM3	75	F (2, 60) = 4.858, p = 0.011*	F (4, 60) = 4.754, p = 0.002**	F (8, 60) = 0.957, p = 0.478
CPF4	75	F (2, 60) = 0.220, p = 0.803	F (4, 60) = 6.455, p <0.001**	F (8, 60) = 0.726, p = 0.668
/ɔ/				
NF2	75	F (2, 60) = 0.753, p = 0.473	F (4, 60) = 3.374, p = 0.015*	F (8, 60) = 1.484, p = 0.182
NM13	75	F (2, 60) = 1.289, p = 0.283	F (4, 60) = 9.060, p < 0.001**	F (8, 60) = 1.290, p = 0.266
NM15	75	F (2, 60) = 0.600, p = 0.552	F (4, 60) = 4.384, p = 0.004**	F (8, 60) = 0.928, p = 0.500
NM16	75	F (2, 60) = 1.409, p = 0.252	F (4, 60) = 4.978, p = 0.002**	F (8, 60) = 1.011, p = 0.437
CPM1	75	F (2, 60) = 1.604, p = 0.210	F (4, 60) = 2.568, p = 0.047**	F (8, 60) = 1.330, p = 0.247
CPM2	75	F (2, 60) = 0.758, p = 0.473	F (4, 60) = 3.374, p = 0.015*	F (8, 60) = 1.484, p = 0.182
CPM3	75	F (2, 60) = 8.562, p < 0.001**	F (4, 60) = 19.78, p < 0.001**	F (8, 60) = 0.642, p = 0.739
CPF4	73†	F (2, 58) = 2.683, p = 0.077	F (4, 58) = 6.832, p < 0.001**	F (8, 58) = 1.796, p = 0.096

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 23

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – SNR

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	75	F (2, 60) = 3.916, p = 0.023*	F (4, 60) = 2.057, p = 0.098	F (8, 60) = 1.256, p = 0.284
NM13	75	F (2, 60) = 1.656, p = 0.199	F (4, 60) = 2.010, p = 0.105	F (8, 60) = 0.641, p = 0.740
NM15	75	F (2, 60) = 1.010, p = 0.370	F (4, 60) = 1.198, p = 0.321	F (8, 60) = 0.938, p = 0.492
NM16	75	F (2, 60) = 3.979, p = 0.024*	F (4, 60) = 14.34, p < 0.001**	F (8, 60) = 0.675, p = 0.712
CPM1	75	F (2, 60) = 0.672, p = 0.514	F (4, 60) = 1.806, p = 0.139	F (8, 60) = 0.543, p = 0.819
CPM2	75	F (2, 60) = 3.916, p = 0.025*	F (4, 60) = 2.057, p = 0.098	F (8, 60) = 1.256, p = 0.284
CPM3	75	F (2, 60) = 2.358, p = 0.103	F (4, 60) = 29.60, p < 0.001**	F (8, 60) = 1.540, p = 0.163
CPF4	72†	F (2, 57) = 1.250, p = 0.294	F (4, 57) = 7.096, p < 0.001**	F (8, 57) = 1.687, p = 0.122
/a/				
NF2	73†	F (2, 58) = 1.892, p = 0.16	F (4, 58) = 10.89, p < 0.001**	F (8, 58) = 1.553, p = 0.159
NM13	75	F (2, 60) =5.740, p = 0.005**	F (4, 60) = 2.844, p = 0.032*	F (8, 60) = 2.771, p = 0.011*
NM15	75	F (2, 60) =0.049, p = 0.953	F (4, 60) = 2.926, p = 0.028*	F (8, 60) = 1.156, p = 0.340
NM16	75	F (2, 60) =0.270, p = 0.764	F (4, 60) = 11.93, p < 0.001**	F (8, 60) = 1.725, p = 0.111
CPM1	74†	F (2, 59) =3.731, p = 0.030*	F (4, 59) = 8.137, p < 0.001**	F (8, 59) = 0.751, p = 0.647
CPM2	73†	F (2, 58) =1.892, p = 0.160	F (4, 58) = 10.89, p < 0.001**	F (8, 58) = 1.553, p = 0.159
CPM3	75	F (2, 60) =4.193, p = 0.020*	F (4, 60) = 18.42, p < 0.001**	F (8, 60) = 2.417, p = 0.025*
CPF4	75	F (2, 60) =0.189, p = 0.829	F (4, 60) = 7.643, p < 0.001**	F (8, 60) = 0.148, p = 0.996
/u/				
NF2	75	F (2, 60) = 2.149, p = 0.125	F (4, 60) = 2.646, p = 0.042*	F (8, 60) = 1.038, p = 0.418
NM13	75	F (2, 60) = 8.660, p < 0.001**	F (4, 60) = 5.185, p = 0.001**	F (8, 60) = 1.027, p = 0.426
NM15	75	F (2, 60) = 0.545, p = 0.583	F (4, 60) = 3.155, p = 0.020*	F (8, 60) = 0.872, p = 0.545
NM16	75	F (2, 60) = 3.080, p = 0.053	F (4, 60) = 19.72, p < 0.001**	F (8, 60) = 0.518, p = 0.838
CPM1	75	F (2, 60) = 1.170, p = 0.317	F (4, 60) = 3.011, p = 0.025*	F (8, 60) = 0.626, p = 0.753
CPM2	75	F (2, 60) = 2.149, p = 0.125	F (4, 60) = 2.646, p = 0.042*	F (8, 60) = 1.038, p = 0.418
CPM3	75	F (2, 60) = 4.167, p = 0.020*	F (4, 60) = 6.808, p < 0.001**	F (8, 60) = 0.711, p = 0.681
CPF4	75	F (2, 60) = 0.176, p = 0.839	F (4, 60) = 10.53, p < 0.001**	F (8, 60) = 1.076, p = 0.392
/ɔ/				
NF2	75	F (2, 60) = 0.596, p = 0.554	F (4, 60) = 4.630, p = 0.003**	F (8, 60) = 2.193, p = 0.041*
NM13	75	F (2, 60) = 0.962, p = 0.388	F (4, 60) = 4.534, p = 0.003**	F (8, 60) = 0.473, p = 0.870
NM15	75	F (2, 60) = 1.147, p = 0.324	F (4, 60) = 2.625, p = 0.043*	F (8, 60) = 1.004, p = 0.443
NM16	75	F (2, 60) = 0.007, p = 0.993	F (4, 60) = 28.51, p < 0.001**	F (8, 60) = 0.940, p = 0.491
CPM1	75	F (2, 60) = 0.599, p = 0.553	F (4, 60) = 4.295, p = 0.004**	F (8, 60) = 1.150, p = 0.344
CPM2	75	F (2, 60) = 0.596, p = 0.554	F (4, 60) = 4.630, p = 0.003**	F (8, 60) = 2.193, p = 0.041*
CPM3	75	F (2, 60) = 7.782, p < 0.001**	F (4, 60) = 32.85, p < 0.001**	F (8, 60) = 1.018, p = 0.433
CPF4	73†	F (2, 58) = 4.657, p = 0.013*	F (4, 58) = 14.44, p < 0.001**	F (8, 58) = 2.241, p = 0.037*

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 24

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – SQ

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	61†	F (2, 46) = 3.913, p = 0.027*	F (4, 46) = 0.315, p = 0.866	F (8, 46) = 0.404, p = 0.912
NM13	72†	F (2, 57) = 0.492, p = 0.614	F (4, 57) = 2.114, p = 0.091	F (8, 57) = 0.646, p = 0.736
NM15	75	F (2, 60) = 0.466, p = 0.630	F (4, 60) = 0.781, p = 0.542	F (8, 60) = 1.235, p = 0.295
NM16	75	F (2, 60) = 0.622, p = 0.540	F (4, 60) = 9.606, p < 0.001**	F (8, 60) = 1.075, p = 0.393
CPM1	58†	F (2, 43) = 0.038, p = 0.963	F (4, 43) = 1.265, p = 0.298	F (8, 43) = 0.476, p = 0.866
CPM2	59†	F (2, 44) = 1.023, p = 0.368	F (4, 44) = 1.397, p = 0.251	F (8, 44) = 1.468, p = 0.197
CPM3	75	F (2, 60) = 0.516, p = 0.600	F (4, 60) = 8.772, p < 0.001**	F (8, 60) = 0.243, p = 0.981
CPF4	59†	F (2, 44) = 2.209, p = 0.122	F (4, 44) = 1.721, p = 0.162	F (8, 44) = 0.695, p = 0.693
/a/				
NF2	64†	F (2, 49) = 0.456, p = 0.637	F (4, 49) = 0.771, p = 0.549	F (8, 49) = 1.042, p = 0.418
NM13	73†	F (2, 58) = 0.672, p = 0.514	F (4, 58) = 0.512, p = 0.727	F (8, 58) = 0.452, p = 0.884
NM15	73†	F (2, 58) = 0.024, p = 0.976	F (4, 58) = 0.532, p = 0.712	F (8, 58) = 0.907, p = 0.517
NM16	69†	F (2, 54) = 0.177, p = 0.838	F (4, 54) = 2.824, p = 0.034	F (8, 54) = 0.685, p = 0.703
CPM1	14†	F (2, 7) = 0.0001, p = 1.000	F (4, 7) = 0.7680, p = 0.579	---
CPM2	36†	F (2, 29) = 0.624, p = 0.543	F (4, 29) = 1.266, p = 0.306	---
CPM3	75	F (2, 60) = 0.288, p = 0.751	F (4, 60) = 6.739, p < 0.001**	F (8, 60) = 0.903, p = 0.520
CPF4	57†	F (2, 42) = 0.256, p = 0.775	F (4, 44) = 1.804, p = 0.146	F (8, 44) = 0.516, p = 0.838
/u/				
NF2	53†	F (2, 38) = 3.302, p = 0.048*	F (4, 38) = 0.368, p = 0.830	F (8, 38) = 2.308, p = 0.040*
NM13	72†	F (2, 57) = 2.203, p = 0.120	F (4, 57) = 5.638, p < 0.001**	F (8, 57) = 0.350, p = 0.942
NM15	65†	F (2, 50) = 1.103, p = 0.340	F (4, 50) = 1.693, p = 0.166	F (8, 50) = 0.552, p = 0.812
NM16	75	F (2, 60) = 2.344, p = 0.105	F (4, 60) = 3.017, p = 0.025*	F (8, 60) = 0.732, p = 0.663
CPM1	61†	F (2, 46) = 0.330, p = 0.721	F (4, 46) = 0.507, p = 0.731	F (8, 46) = 0.250, p = 0.978
CPM2	65†	F (2, 50) = 1.790, p = 0.178	F (4, 50) = 0.309, p = 0.871	F (8, 50) = 0.331, p = 0.950
CPM3	75	F (2, 60) = 1.069, p = 0.350	F (4, 60) = 7.269, p < 0.001**	F (8, 60) = 1.435, p = 0.201
CPF4	61†	F (2, 46) = 0.271, p = 0.764	F (4, 46) = 2.000, p = 0.110	F (8, 46) = 0.383, p = 0.924
/ɔ/				
NF2	61†	F (2, 46) = 6.005, p = 0.005**	F (4, 46) = 0.238, p = 0.915	F (8, 46) = 1.442, p = 0.205
NM13	59†	F (2, 44) = 0.407, p = 0.668	F (4, 44) = 2.780, p = 0.038*	F (8, 44) = 0.841, p = 0.572
NM15	22†	F (2, 15) = 0.403, p = 0.675	F (4, 15) = 0.567, p = 0.690	---
NM16	71†	F (2, 56) = 0.012, p = 0.988	F (4, 56) = 2.817, p = 0.034*	F (8, 56) = 0.888, p = 0.533
CPM1	51†	F (2, 36) = 1.064, p = 0.356	F (4, 36) = 0.443, p = 0.777	F (8, 36) = 0.928, p = 0.505
CPM2	62†	F (2, 47) = 0.696, p = 0.503	F (4, 47) = 0.748, p = 0.565	F (8, 47) = 0.405, p = 0.912
CPM3	75	F (2, 60) = 1.308, p = 0.278	F (4, 60) = 4.371, p = 0.004**	F (8, 60) = 1.582, p = 0.150
CPF4	56†	F (2, 41) = 1.603, p = 0.214	F (4, 41) = 2.598, p = 0.050*	F (8, 44) = 2.786, p = 0.015*

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 25

Results of Two-way ANOVAs for the non-speech data from 4 controls and 4 CP subjects – OQ

Subject	N	Place of Articulation	Position	Place of Articulation x Position
/i/				
NF2	61†	F (2, 46) = 2.208, p = 0.121	F (4, 46) = 0.436, p = 0.782	F (8, 46) = 0.307, p = 0.960
NM13	72†	F (2, 57) = 0.300, p = 0.742	F (4, 57) = 2.454, p = 0.056	F (8, 57) = 0.644, p = 0.738
NM15	75	F (2, 60) = 0.615, p = 0.544	F (4, 60) = 1.245, p = 0.302	F (8, 60) = 1.423, p = 0.206
NM16	75	F (2, 60) = 0.818, p = 0.446	F (4, 60) = 12.81, p < 0.001**	F (8, 60) = 0.837, p = 0.574
CPM1	58†	F (2, 43) = 0.071, p = 0.932	F (4, 43) = 0.867, p = 0.492	F (8, 43) = 0.430, p = 0.896
CPM2	59†	F (2, 44) = 3.231, p = 0.049*	F (4, 44) = 1.450, p = 0.234	F (8, 44) = 1.256, p = 0.291
CPM3	75	F (2, 60) = 0.265, p = 0.768	F (4, 60) = 10.30, p < 0.001**	F (8, 60) = 0.245, p = 0.980
CPF4	59†	F (2, 44) = 2.053, p = 0.140	F (4, 44) = 1.893, p = 0.129	F (8, 44) = 0.751, p = 0.647
/a/				
NF2	64†	F (2, 49) = 0.587, p = 0.560	F (4, 49) = 0.771, p = 0.588	F (8, 49) = 1.135, p = 0.357
NM13	73†	F (2, 58) = 0.510, p = 0.603	F (4, 58) = 0.577, p = 0.680	F (8, 58) = 0.518, p = 0.838
NM15	73†	F (2, 58) = 0.006, p = 0.994	F (4, 58) = 0.521, p = 0.721	F (8, 58) = 1.184, p = 0.325
NM16	69†	F (2, 54) = 0.258, p = 0.773	F (4, 54) = 2.775, p = 0.036*	F (8, 54) = 0.744, p = 0.652
CPM1	14†	F (2, 7) = 0.0011, p = 0.999	F (4, 7) = 0.2800, p = 0.882	---
CPM2	36†	F (2, 29) = 0.614, p = 0.548	F (4, 29) = 1.827, p = 0.151	---
CPM3	75	F (2, 60) = 0.355, p = 0.703	F (4, 60) = 2.597, p = 0.045*	F (8, 60) = 0.645, p = 0.737
CPF4	57†	F (2, 42) = 0.504, p = 0.608	F (4, 44) = 2.186, p = 0.087	F (8, 44) = 0.467, p = 0.872
/u/				
NF2	53†	F (2, 38) = 3.326, p = 0.047*	F (4, 38) = 0.900, p = 0.474	F (8, 38) = 2.282, p = 0.042*
NM13	72†	F (2, 57) = 1.721, p = 0.188	F (4, 57) = 5.258, p = 0.001**	F (8, 57) = 0.179, p = 0.993
NM15	65†	F (2, 50) = 0.778, p = 0.465	F (4, 50) = 1.887, p = 0.127	F (8, 50) = 0.464, p = 0.875
NM16	75	F (2, 60) = 4.389, p = 0.017*	F (4, 60) = 3.523, p = 0.012*	F (8, 60) = 0.763, p = 0.637
CPM1	61†	F (2, 46) = 0.532, p = 0.591	F (4, 46) = 0.795, p = 0.534	F (8, 46) = 0.166, p = 0.994
CPM2	65†	F (2, 50) = 2.350, p = 0.106	F (4, 50) = 0.331, p = 0.855	F (8, 50) = 0.475, p = 0.868
CPM3	75	F (2, 60) = 1.834, p = 0.169	F (4, 60) = 9.540, p < 0.001**	F (8, 60) = 1.980, p = 0.065
CPF4	61†	F (2, 46) = 0.328, p = 0.722	F (4, 46) = 2.396, p = 0.064	F (8, 46) = 0.391, p = 0.920
/ɔ/				
NF2	61†	F (2, 46) = 5.099, p = 0.010*	F (4, 46) = 0.589, p = 0.672	F (8, 46) = 1.871, p = 0.088
NM13	59†	F (2, 44) = 0.615, p = 0.545	F (4, 44) = 3.057, p = 0.026*	F (8, 44) = 0.872, p = 0.547
NM15	22†	F (2, 15) = 0.246, p = 0.785	F (4, 15) = 0.602, p = 0.607	---
NM16	71†	F (2, 56) = 0.087, p = 0.917	F (4, 56) = 4.375, p = 0.004**	F (8, 56) = 1.161, p = 0.339
CPM1	51†	F (2, 36) = 0.875, p = 0.425	F (4, 36) = 0.210, p = 0.931	F (8, 36) = 0.702, p = 0.687
CPM2	62†	F (2, 47) = 0.932, p = 0.401	F (4, 47) = 1.122, p = 0.358	F (8, 47) = 0.470, p = 0.871
CPM3	75	F (2, 60) = 1.805, p = 0.173	F (4, 60) = 3.546, p = 0.012*	F (8, 60) = 1.411, p = 0.211
CPF4	56†	F (2, 41) = 1.821, p = 0.175	F (4, 41) = 2.747, p = 0.041*	F (8, 44) = 3.203, p = 0.006*

*Significant at 0.05 level

**Significant at 0.005 level

†Missing data

Appendix 26

Two-way ANOVA results for the non-speech data from individuals in the control group – maximum jaw displacement

Subject	N	Place of Articulation Effect	Position Effect	Place x Position Interaction Effect
/i/				
NF1	45	F(2, 36) = 5.327, p = 0.009*	F(2, 36) = 1.079, p < 0.351	F(4, 36) = 0.721, p = 0.583
NF2	45	F(2, 36) = 11.34, p < 0.001**	F(2, 36) = 2.861, p = 0.070	F(4, 36) = 0.880, p = 0.486
NF3	45	F(2, 36) = 0.970, p = 0.389	F(2, 36) = 0.785, p = 0.464	F(4, 36) = 1.473, p = 0.231
NF4	45	F(2, 36) = 1.447, p = 0.249	F(2, 36) = 1.859, p = 0.170	F(4, 36) = 1.443, p = 0.240
NM5	45	F(2, 36) = 0.570, p = 0.571	F(2, 36) = 0.507, p = 0.607	F(4, 36) = 1.284, p = 0.295
NM6	45	F(2, 36) = 0.989, p = 0.382	F(2, 36) = 1.350, p = 0.272	F(4, 36) = 1.271, p = 0.299
NM7	45	F(2, 36) = 0.662, p = 0.522	F(2, 36) = 1.755, p = 0.188	F(4, 36) = 0.190, p = 0.942
NF8	45	F(2, 36) = 1.794, p = 0.181	F(2, 36) = 0.075, p = 0.928	F(4, 36) = 0.713, p = 0.588
NF9	43[†]	F(2, 34) = 0.275, p = 0.761	F(2, 34) = 1.287, p = 0.289	F(4, 34) = 0.062, p = 0.992
NM10	45	F(2, 36) = 2.202, p = 0.125	F(2, 36) = 0.822, p = 0.448	F(4, 36) = 0.075, p = 0.989
NF11	45	F(2, 36) = 10.51, p < 0.001**	F(2, 36) = 0.217, p = 0.806	F(4, 36) = 1.760, p = 0.158
NM12	44[†]	F(2, 35) = 3.078, p = 0.059	F(2, 35) = 2.693, p = 0.082	F(4, 35) = 0.586, p = 0.675
NM13	44[†]	F(2, 35) = 1.092, p = 0.347	F(2, 35) = 0.200, p = 0.820	F(4, 35) = 0.374, p = 0.826
NF14	45	F(2, 36) = 8.728, p < 0.001**	F(2, 36) = 0.650, p = 0.528	F(4, 36) = 0.981, p = 0.430
NM15	45	F(2, 36) = 11.34, p < 0.001**	F(2, 36) = 2.861, p = 0.070	F(4, 36) = 0.880, p = 0.486
NM16	45	F(2, 36) = 0.159, p = 0.854	F(2, 36) = 1.283, p = 0.290	F(4, 36) = 1.572, p = 0.203
/a/				
NF1	45	F(2, 36) = 1.271, p = 0.292	F(2, 36) = 2.329, p < 0.112	F(4, 36) = 2.068, p = 0.105
NF2	45	F(2, 36) = 1.321, p = 0.280	F(2, 36) = 1.681, p = 0.200	F(4, 36) = 1.190, p = 0.332
NF3	45	F(2, 36) = 0.808, p = 0.454	F(2, 36) = 0.105, p = 0.901	F(4, 36) = 0.288, p = 0.884
NF4	45	F(2, 36) = 1.147, p = 0.329	F(2, 36) = 4.617, p = 0.016*	F(4, 36) = 0.777, p = 0.548
NM5	45	F(2, 36) = 3.382, p = 0.045*	F(2, 36) = 1.121, p = 0.337	F(4, 36) = 1.158, p = 0.346
NM6	45	F(2, 36) = 6.760, p = 0.003**	F(2, 36) = 0.578, p = 0.566	F(4, 36) = 0.617, p = 0.653
NM7	45	F(2, 36) = 0.632, p = 0.538	F(2, 36) = 0.066, p = 0.937	F(4, 36) = 0.863, p = 0.495
NF8	45	F(2, 36) = 0.435, p = 0.651	F(2, 36) = 0.764, p = 0.474	F(4, 36) = 0.529, p = 0.715
NF9	43[†]	F(2, 35) = 6.495, p = 0.004**	F(2, 35) = 0.267, p = 0.767	F(4, 35) = 0.184, p = 0.945
NM10	45	F(2, 36) = 4.202, p = 0.023*	F(2, 36) = 2.294, p = 0.115	F(4, 36) = 0.098, p = 0.982
NF11	45	F(2, 36) = 8.500, p < 0.001**	F(2, 36) = 1.292, p = 0.287	F(4, 36) = 0.871, p = 0.491
NM12	45	F(2, 36) = 0.083, p = 0.921	F(2, 36) = 0.013, p = 0.987	F(4, 36) = 0.910, p = 0.468
NM13	45	F(2, 36) = 0.376, p = 0.689	F(2, 36) = 1.131, p = 0.334	F(4, 36) = 0.517, p = 0.723
NF14	45	F(2, 36) = 11.16, p < 0.001**	F(2, 36) = 4.179, p = 0.023*	F(4, 36) = 0.154, p = 0.960
NM15	45	F(2, 36) = 1.321, p = 0.280	F(2, 36) = 1.681, p = 0.200	F(4, 36) = 1.190, p = 0.332
NM16	45	F(2, 36) = 12.74, p < 0.001**	F(2, 36) = 1.994, p = 0.151	F(4, 36) = 1.132, p = 0.357
/u/				
NF1	45	F(2, 36) = 1.443, p = 0.250	F(2, 36) = 0.204, p = 0.816	F(4, 36) = 0.358, p = 0.837
NF2	45	F(2, 36) = 5.489, p = 0.008*	F(2, 36) = 0.429, p = 0.655	F(4, 36) = 0.767, p = 0.554
NF3	45	F(2, 36) = 1.867, p = 0.169	F(2, 36) = 1.246, p = 0.300	F(4, 36) = 1.627, p = 0.189
NF4	45	F(2, 36) = 3.346, p = 0.046*	F(2, 36) = 4.741, p = 0.015*	F(4, 36) = 0.957, p = 0.443
NM5	45	F(2, 36) = 0.776, p = 0.468	F(2, 36) = 0.508, p = 0.606	F(4, 36) = 2.150, p = 0.095
NM6	45	F(2, 36) = 1.436, p = 0.252	F(2, 36) = 0.001, p = 0.999	F(4, 36) = 0.731, p = 0.577
NM7	45	F(2, 36) = 0.355, p = 0.704	F(2, 36) = 17.66, p < 0.001**	F(4, 36) = 0.068, p = 0.991
NF8	45	F(2, 36) = 4.037, p = 0.026*	F(2, 36) = 0.219, p = 0.804	F(4, 36) = 0.745, p = 0.568
NF9	40[†]	F(2, 31) = 0.040, p = 0.961	F(2, 31) = 1.354, p = 0.273	F(4, 31) = 1.070, p = 0.388
NM10	44[†]	F(2, 35) = 1.103, p = 0.343	F(2, 35) = 0.305, p = 0.739	F(4, 35) = 0.918, p = 0.465
NF11	45	F(2, 36) = 0.710, p = 0.498	F(2, 36) = 0.104, p = 0.902	F(4, 36) = 0.765, p = 0.555
NM12	45	F(2, 36) = 0.679, p = 0.513	F(2, 36) = 0.353, p = 0.705	F(4, 36) = 0.823, p = 0.519
NM13	45	F(2, 36) = 2.978, p = 0.064	F(2, 36) = 3.469, p = 0.042*	F(4, 36) = 1.794, p = 0.152
NF14	45	F(2, 36) = 3.569, p = 0.039*	F(2, 36) = 11.53, p < 0.001**	F(4, 36) = 1.359, p = 0.267
NM15	45	F(2, 36) = 5.489, p = 0.008*	F(2, 36) = 0.429, p = 0.655	F(4, 36) = 0.767, p = 0.554
NM16	45	F(2, 36) = 2.075, p = 0.140	F(2, 36) = 0.857, p = 0.433	F(4, 36) = 3.873, p = 0.010*
/ɔ/				
NF1	45	F(2, 36) = 0.494, p = 0.614	F(2, 36) = 0.556 p = 0.578	F(4, 36) = 0.464, p = 0.761
NF2	45	F(2, 36) = 4.166, p = 0.024*	F(2, 36) = 0.363, p = 0.698	F(4, 36) = 0.291, p = 0.882
NF3	45	F(2, 36) = 7.514, p = 0.002**	F(2, 36) = 1.092, p = 0.346	F(4, 36) = 0.972, p = 0.435
NF4	45	F(2, 36) = 3.024, p = 0.061	F(2, 36) = 0.601, p = 0.554	F(4, 36) = 0.437, p = 0.781
NM5	45	F(2, 36) = 2.004, p = 0.150	F(2, 36) = 0.207, p = 0.814	F(4, 36) = 0.412, p = 0.799
NM6	45	F(2, 36) = 1.388, p = 0.263	F(2, 36) = 2.129, p = 0.134	F(4, 36) = 1.263, p = 0.302
NM7	44[†]	F(2, 35) = 3.394, p = 0.045*	F(2, 36) = 1.031, p = 0.367	F(4, 36) = 1.304, p = 0.287
NF8	45	F(2, 36) = 0.021, p = 0.979	F(2, 36) = 1.570, p = 0.222	F(4, 36) = 0.338, p = 0.851
NF9	38[†]	F(2, 29) = 1.450, p = 0.251	F(2, 29) = 4.610, p = 0.018*	F(4, 29) = 1.509, p = 0.226
NM10	44[†]	F(2, 35) = 0.338, p = 0.716	F(2, 35) = 2.087, p = 0.139	F(4, 35) = 1.417, p = 0.249
NF11	45	F(2, 36) = 1.744, p = 0.189	F(2, 36) = 0.220, p = 0.804	F(4, 36) = 0.874, p = 0.489
NM12	45	F(2, 36) = 1.760, p = 0.187	F(2, 36) = 8.166, p = 0.001**	F(4, 36) = 1.169, p = 0.341
NM13	44[†]	F(2, 35) = 2.043, p = 0.145	F(2, 35) = 0.929, p = 0.404	F(4, 35) = 0.767, p = 0.554
NF14	45	F(2, 36) = 9.259, p < 0.001**	F(2, 36) = 1.791, p = 0.181	F(4, 36) = 3.007, p = 0.031*
NM15	45	F(2, 36) = 4.166, p = 0.024*	F(2, 36) = 0.363, p = 0.698	F(4, 36) = 0.291, p = 0.882
NM16	45	F(2, 36) = 11.03, p < 0.001**	F(2, 36) = 0.907, p = 0.413	F(4, 36) = 0.566, p = 0.689

Appendix 27

Results of Two-way ANOVAs for the non-speech data from 4 CP subjects – maximum jaw displacement

Subject	N	Place of Articulation Effect	Position Effect	Place of Articulation x Position
/i/				
CPM1	45	F(2, 36) = 0.762, p = 0.474	F(2, 36) = 0.839, p = 0.441	F(4, 36) = 1.268, p = 0.301
CPM2	34†	F(2, 25) = 0.678, p = 0.516	F(2, 25) = 1.105, p = 0.347	F(4, 25) = 3.849, p = 0.014*
CPM3	45	F(2, 36) = 0.859, p = 0.432	F(2, 36) = 2.703, p = 0.081	F(4, 36) = 0.692, p = 0.602
CPF4	42†	F(2, 33) = 1.174, p = 0.322	F(2, 33) = 0.302, p = 0.742	F(4, 33) = 1.590, p = 0.200
/a/				
CPM1	45	F(2, 36) = 1.005, p = 0.376	F(2, 36) = 1.101, p = 0.343	F(4, 36) = 0.231, p = 0.919
CPM2	40†	F(2, 31) = 1.619, p = 0.214	F(2, 31) = 1.403, p = 0.261	F(4, 31) = 0.225, p = 0.922
CPM3	45	F(2, 36) = 3.544, p = 0.039*	F(2, 36) = 1.501, p = 0.237	F(4, 36) = 0.485, p = 0.746
CPF4	43†	F(2, 34) = 3.656, p = 0.036*	F(2, 34) = 1.029, p = 0.368	F(4, 34) = 1.062, p = 0.390
/u/				
CPM1	39†	F(2, 30) = 2.002, p = 0.153	F(2, 30) = 0.087, p = 0.917	F(4, 30) = 0.229, p = 0.920
CPM2	42†	F(2, 33) = 7.287, p = 0.002**	F(2, 33) = 0.149, p = 0.862	F(4, 33) = 0.975, p = 0.434
CPM3	39†	F(2, 30) = 0.060, p = 0.942	F(2, 30) = 3.069, p = 0.061	F(4, 30) = 0.302, p = 0.874
CPF4	44†	F(2, 35) = 0.466, p = 0.631	F(2, 35) = 0.189, p = 0.829	F(4, 35) = 0.291, p = 0.882
/ɔ/				
CPM1	39†	F(2, 30) = 0.770, p = 0.472	F(2, 30) = 2.226, p = 0.126	F(4, 30) = 0.814, p = 0.526
CPM2	42†	F(2, 33) = 4.812, p = 0.015*	F(2, 33) = 0.928, p = 0.405	F(4, 33) = 0.512, p = 0.727
CPM3	45	F(2, 36) = 0.648, p = 0.529	F(2, 36) = 1.633, p = 0.210	F(4, 36) = 2.285, p = 0.079
CPF4	44†	F(2, 35) = 5.483, p = 0.008	F(2, 35) = 0.888, p = 0.420	F(4, 35) = 2.050, p = 0.109

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data