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The Effects of Laryngeal Activity on Articulatory Kinematics

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ABSTRACT

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The current study examined the effects of three speech conditions (voiced, whispered, mouthed) on articulatory kinematics at the sentence and word level. Participants included 20 adults (10 males, 10 females) with no history of speech, language, or hearing disorders. Participants read aloud six target utterances in the three different speaking conditions while articulatory kinematics were measured using the NDI Wave electromagnetic articulograph. The following articulators were examined: mid tongue, front of tongue, jaw, lower lip, and upper lip. One of the target utterances was chosen for analysis (*It's time to shop for two new suits*) at the sentence level and then further segmented for more detailed analysis of the word *time*. Results revealed a number of significant changes between the voiced and mouthed conditions for all articulators at the sentence level. Significant increases in sentence duration, articulatory stroke count, and stroke duration as well as significant decreases in peak stroke speed, stroke distance, and hull volume were found in the mouthed condition at the sentence level when compared to the voiced condition. Peak velocity significantly decreased in the mouthed condition at the word level, but overall the sentence level measures were more sensitive to change. These findings suggest that both laryngeal activation and auditory feedback may be necessary in the production of normally articulate speech, and that the absence of these may account for the significant changes between the voiced and mouthed conditions.

Keywords: phonation, whisper, articulatory kinematics, coordination

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF APPENDICES

Appendix Page

DESCRIPTION OF STRUCTURE AND CONTENT

This document is structured after recent peer-reviewed communication disorders journal articles. Appendix A consists of an annotated bibliography. Appendix B consists of the informed consent document approved by the Institutional Review Board and signed by each participant.

Introduction

The larynx and vocal tract are often viewed as two separate components that are necessary to produce speech. The larynx is the source of sound, which is generated as air from the lungs drives the vibration of the vocal folds. The larynx produces a fundamental frequency and its harmonics (the source spectrum). As this complex sound spectrum enters the vocal tract, the individual frequency components are filtered (resonated selectively) based on the shape of the vocal tract cavities. The length and cross-sectional area of the vocal tract are continually changing because of the movement of the articulators (Behrman, 2013).

Although the larynx and oral cavity have their own specific roles in speech production, studies have examined the interaction of both subsystems in the production of intelligible speech. A 1995 case study reported the effects of high effort voice treatment in a man diagnosed with the early stages of Parkinson Disease (PD; Dromey, Ramig, & Johnson, 1995). He participated in the Lee Silverman Voice Treatment (LSVT) over a four-week period; pre- and post-treatment data were analyzed. LVST is a therapy technique developed to benefit persons with hypokinetic dysarthria and focuses on increasing vocal intensity of the patient by targeting respiratory and laryngeal function in speech. When comparing pre- and post-treatment data, the authors not only found the anticipated increase in vocal intensity, but also evidence of improved articulation, which had not been directly targeted. Specifically, they found that in post-treatment data the duration for whole words and vowels increased; frication duration decreased; rise time decreased; and second formant transition duration, extent, and rate for all words increased. This study showed that treatment-related changes in the activity of the larynx were associated with concurrent improvements in vocal tract activity; in other words, there was beneficial change in articulation when only the voice was directly targeted in therapy.

Other studies have revealed similar changes in articulatory activity when a laryngeal disorder had been directly treated (Cannito, 2004; Dromey, 2010; Dromey, Nissen, Roy, & Merrill, 2008; Dromey, Reese, & Howey, 2007; Tingley & Dromey, 2000). Spasmodic dysphonia (SD) is a neurological voice disorder, which disturbs vocal quality, primarily during connected speech. There is no known etiology or cure for SD, but a temporary reduction in the frequency and severity of vocal spasms has been documented with the injection of Botox (botulinum toxin) into the patient's thyroarytenoid muscle. Cannito et al. (2004) studied 42 patients pre- and post-Botox injection to explore the effect of this treatment on vocal quality and speech fluency. They found that both improved after the injection of Botox, providing further evidence that treatment of the voice can influence vocal tract behavior.

Tingley et al. (2000) also investigated the link between disordered laryngeal and articulatory movements in persons with SD and the effects on articulatory movement in voiced and whispered conditions. Speakers with SD were compared to a control group consisting of individuals with no history of voice disorders. Lip trajectories during voiced and whispered conditions were compared between the two groups. Although SD is generally viewed as a laryngeal disorder, analysis of data from this study showed disturbances in articulatory activity in the SD group compared with those in the control group. Comparisons revealed a difference in the count of velocity peaks when opening-closing gestures were measured. Previous authors (Adams, Weismer, & Kent, 1993) have noted that the count of velocity peaks tends to increase for slower or disordered speech. Those with SD in the Tingley et al. (2000) study displayed multiple velocity peaks, while the control groups presented with only one velocity peak for the same movement. This finding implied that participants in the SD group presented with articulatory movements that were less smoothly controlled, with elevated instability during speech production. Tingley and Dromey also documented that when participants were asked to whisper, speakers with SD showed a decrease in the count of velocity peaks and became more comparable to normal speakers in their articulatory movements. The results of this experiment suggest that when vocal spasms are absent in the whispered condition, articulatory movements are more normal. A later study examined the lip movement changes pre-and post-Botox injection for individuals with SD. Before Botox injections these speakers had irregular lip movement patterns, which became more normal after Botox treatment. This work demonstrated that treatment centered on improved laryngeal function can also result in improved articulation (Dromey et al., 2007). Thus, the nature of the laryngeal activity can influence articulatory movements.

This influence of laryngeal activity on articulatory behavior has also been observed in the treatment of Muscle Tension Dysphonia (MTD), which is a functional voice disorder that negatively impacts vocal quality due to excessive laryngeal muscle tension during speech. When treating MTD, most therapy is focused on decreasing laryngeal tension and teaching correct voice behaviors. Treatment can include circumlaryngeal massage and laryngeal reposturing, but in all cases treatment is focused solely on improving the voice. One study investigated the impact of voice treatment on over 100 patients with MTD, and included articulatory acoustic measures in addition to voice outcomes. The results indicated that after participating in circumlaryngeal massage, all participants showed improvement in perceptual vocal quality, but also exhibited improved articulatory fluency as measured by changes in speech/pause ratios during a reading task. This study also found that diphthong extent and rate increased after laryngeal treatment. Thus it showed that through MTD treatment aimed at reducing laryngeal tension, articulator movement increased (Dromey et al., 2008).

While these studies explored the effects of voice treatment on the behavior of the articulators, Munhall, Löfqvist, and Kelso (1994) investigated changes in laryngeal activity during unanticipated articulatory disturbances. Lip, jaw, and laryngeal movements were recorded while participants were instructed to repeat a nonsense phrase (*/i'pip/ again*) 400 times. Perturbations were intermittently introduced to the lower lip while participant were speaking between the first vowel and voiceless consonant. Results revealed not only disturbances to articulatory movements, but the larynx also reacted with delayed vocal fold abduction and increased vocal fold adduction. This study revealed aspects of the complex relationship between the vocal tract and the larynx. When the activity of either structure is disturbed, the consequences can be manifest in both.

In the production of speech not only is there a complex relationship between the larynx and vocal tract but also between the articulators themselves. Accurate articulatory sequencing, velocity, displacement, and coordination are essential in the production of vowels and consonants. All vowels are formed with a relatively open mouth, and differ only in articulatory placement. Consonants differ not only in articulatory placement but also the formation of precise vocal tract constrictions and also the presence or absence of vocal fold oscillation. The current study explored this complex process, including details of articulator movement, during speech production at the sentence and word level as laryngeal behavior was adjusted.

A study by Caruso, Abbs, and Gracco (1988) explored the coordination between the upper lip, lower lip, and jaw in a group that stuttered compared to a normally fluent control group. Participants were instructed to repeat the nonsense word *sapapple* while articulatory movements were measured. Only fluent utterances from the stuttering group were analyzed and compared to the control group samples. The results showed that normal speakers had consistent sequencing of the upper lip, lower lip, and jaw when producing the target word. This same precise sequencing was not found in the stuttering group, which suggests that inconsistent sequencing between articulatory movements can influence the effectiveness of speech output.

The current study explored the relationship between the larynx and the vocal tract when different laryngeal behaviors were introduced. The laryngeal behaviors investigated were normal voice, whisper, and silent mouthing. We predicted that the articulatory movements would vary across the three speech conditions chosen for analysis, based on the studies reviewed above, which documented the interactions between laryngeal and articulatory activity.

Methods

Participants

Ten males (ages 20-32, *M* = 25.3, *SD* = 3.4) and 10 females (ages 20-34, *M* = 25.1, *SD* = 4.0) from the Brigham Young University community participated in this study. All were native English speakers and reported no history of speech, language, or hearing disorders. Participants were recruited by word of mouth among the acquaintances of the experimenters. Prior to participation, each signed a consent form, which had been approved by the Brigham Young University Institutional Review Board. Participants received a $10 compensation for taking part in the study.

Equipment

Participants were seated in a single-walled sound booth for the recordings. A condenser microphone (AKG C2000B, Vienna, Austria) was used to record participants' utterances. The microphone signal was calibrated with a sound level meter to allow measures of speech intensity. Articulatory kinematics were recorded using the NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada). The first two channels carried the signals from a reference sensor, which was glued to an eyeglass frame without lenses that participants then wore throughout the study. Five additional channels of data were collected by attaching 3 mm sensor coils at midline to the following articulators: mid tongue (halfway back from the tip - TM), front of tongue (1 cm back from the tip - TF), mandibular central incisors to measure jaw movement (J), lower vermillion border of the lower lip (LL), and upper vermillion border of the upper lip (UL). The coils were attached with PerAcryl 90 viscous glue (GluStich, Delta, British Columbia, Canada). Sensors reported x, y, and z positions of the articulators in real time through the Wavefront software to a computer located outside the sound booth. Movement data were collect at a rate of 400 Hz and audio was recorded at a sampling rate of 22050 Hz.

Procedure and Speech Tasks

Once the sensors were attached to the articulators, participants were instructed to speak continuously for 20 minutes by reading a newspaper or magazine, talking with the researchers, and practicing sentences for a separate study of adaptation. After this adjustment period, participants read six stimulus sentences, which included a variety of vowel and consonant sounds that required complex articulatory movements. Participants read aloud the utterances that are listed in Table 1. Each sentence was repeated four times. Participants produced the 24 utterances in each of the following five conditions: normal voice (determined by the participant), whispered speech (perceptually verified by the experimenters), mouthed (with the sentence number spoken aloud to facilitate subsequent segmentation), soft voice (perceptually verified by the experimenters, and loud voice (perceptually verified by the experimenters). The order of the conditions was randomized separately for each participant.

Table 1

Sentences Read by Each Participant in the Three Different Speaking Conditions

Sentences
It's time to shop for two new suits.
A good AC should keep your car cool.
It's never too soon to choose the right.
One warm morning a boy was mowing the lawn.
We do agree the loud noise is annoying.
There's no good reason they would go down there.

Data Analysis

The experimenters began by evaluating the first sentence produced by participants: *It's time to shop for two new suits*. This sentence was segmented from the other five sentences using a custom Matlab application as shown in Figure 1. Measures from the first three error-free repetitions of the four for each sentence in each speaking condition were averaged prior to statistical analysis. At the sentence level, the following measures were computed: sentence duration, number of articulator movement strokes, the average of the stroke peak speeds for all strokes in the sentence, average stroke distance, and average stroke duration (Tasko & Westbury, 2002). These metrics were calculated from the speed plots shown in Figure 2. The speed plots were generated in Matlab using the x and y positions of each sensor over time. The two-dimensional area encompassed by the movement of the articulatory sensors during the production of the sentence (convex hull operation in Matlab) was also computed as illustrated in Figure 3.

The experimenters then narrowed the analysis to the word level. The word *time* was chosen for all word level metrics. The word was segmented from the sentence *It's time to shop for two new suits* using Matlab, as displayed with the green vertical lines in Figure 1. *Time* was selected because of the posterior and anterior lingual displacement necessary in the production of the initial alveolar consonant and the subsequent diphthong. There is also a bilabial at the conclusion of the word, which allows for measurement of the displacement of the jaw, upper lip, and lower lip. Within this one syllable word, we examined the relative timing (as a proportion of the word duration) of vertical velocity peaks for each of the five-sensor recordings shown in Figure 4, as well as the peak velocity (mm/s) for each sensor. Measures were also computed to reflect the distance traveled and area covered by each articulator as well as the correlation between the following articulator movements: J/TM, J/TF, TM/TF, J/LL, and LL/UL.

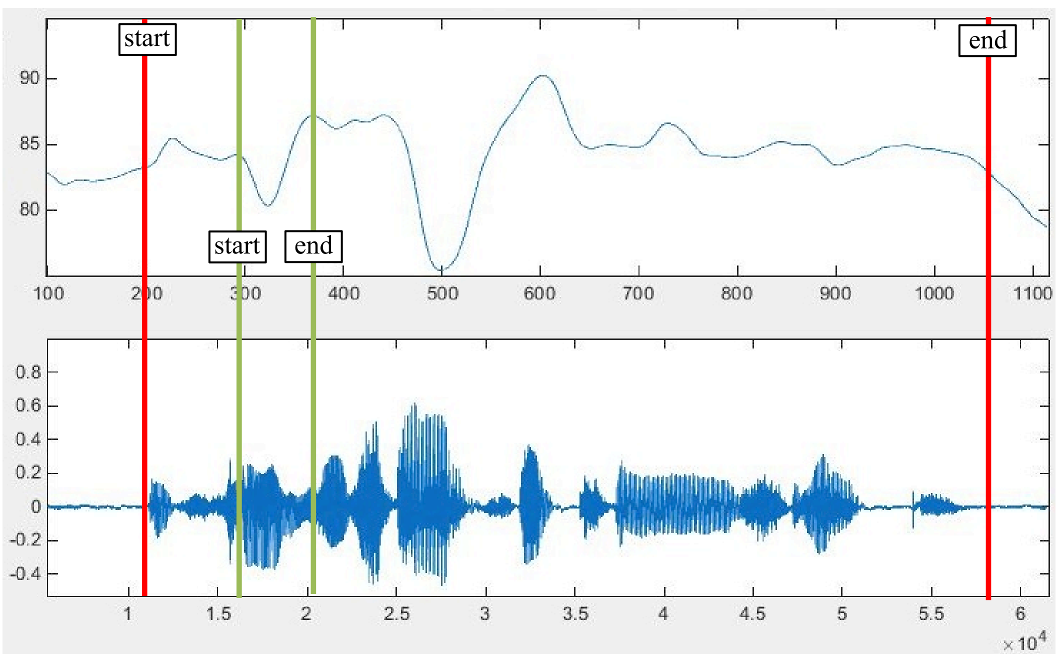

Figure 1. Sample sentence segmentation points. The red bars show the acoustic/perceptual segmentation of the sentence *It's time to shop for two new suits* from participant F2. The green bars show the points of segmentation of the word *time* from participant F2 from the peaks in the kinematic record. The top display shows the vertical displacement of the front tongue marker (TF). The bottom display is the microphone waveform for the sentence.

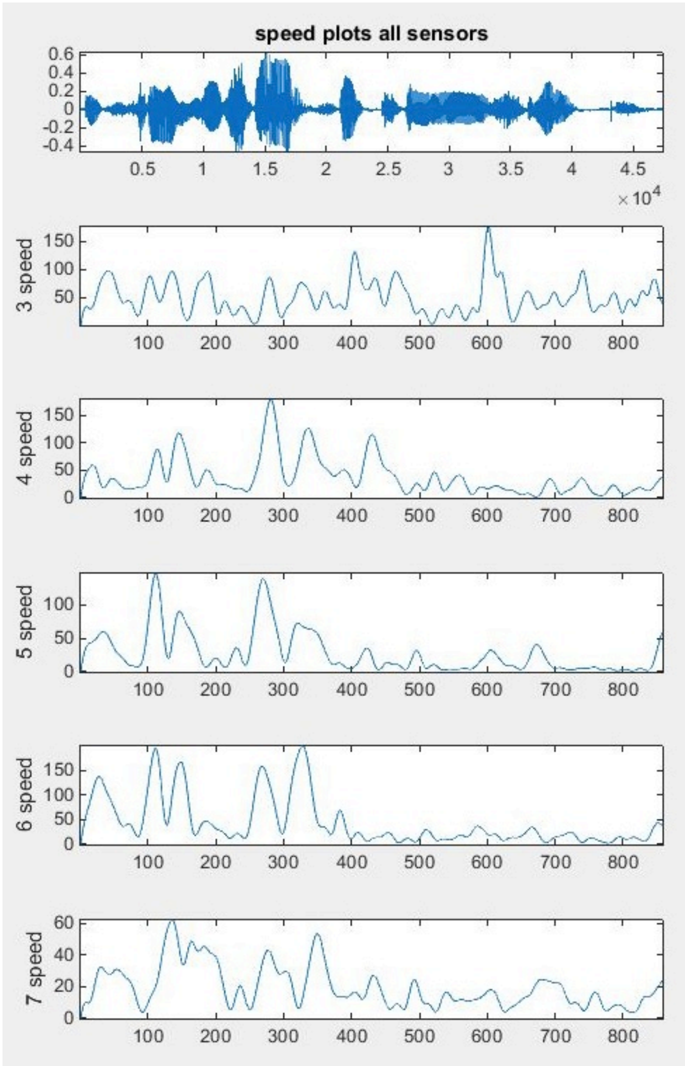

Figure 2. Speed plots at the sentence level. The top panel shows the microphone waveform that is time aligned with all the sensor speed plots displayed in the lower five panels. These data were used to calculate sentence duration, number of articulator movement strokes, average stroke peak speed, and average stroke distance for each sensor at the sentence level.

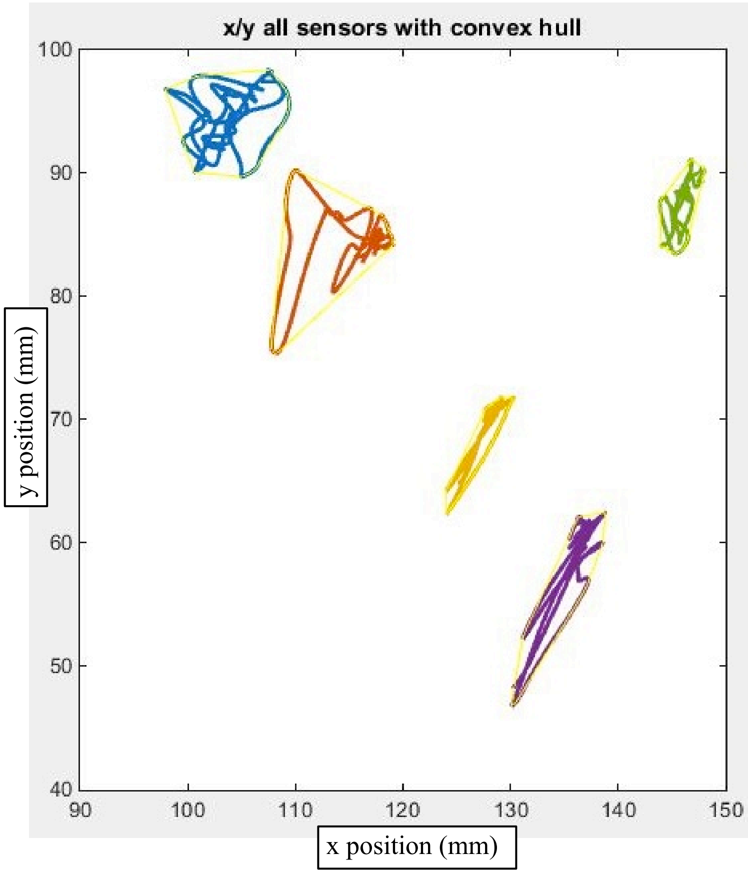

Figure 3. Convex hull of all sensors at the sentence level. This figure demonstrates the overall area (within the yellow line) covered by each articulator in the x and y dimensions during the sentence production.

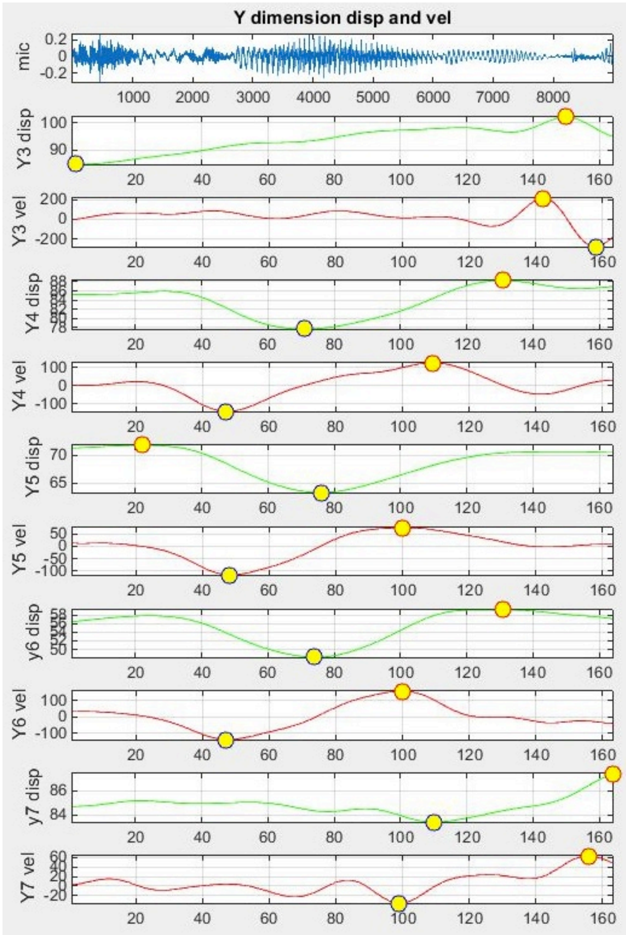

Figure 4. Vertical displacement and velocity at the word level. The top panel shows the microphone waveform that is time aligned with displacement and velocity plots for the lower 10 panels. On the green displacement plots, yellow points identify the minimum and maximum vertical displacement of each articulator during word production. Yellow points on the red velocity graphs indicate the maximum downward velocity and upward velocity of each articulator during the word *time*.

Reliability

To address measurement reliability in the segmentation process, all data were segmented at least twice by the experimenter at the sentence and word level across all conditions. The dependent measures derived from both segmentations were recorded in two separate documents, which were then compared. Another experimenter statistically analyzed each variable for the two measurement sets and found a correlation of 1.0 for all measures and speaking conditions. This was not unexpected given that Matlab automatically calculated the measures once the experimenter set the segmentation points.

Results

Both sentence and word data were tested using a repeated measures ANOVA with concurrent contrasts and included gender as a factor. When significant violations of the sphericity assumption were found with the Mauchly's Test, the Huynh-Feldt results were reported, which relied on non-integer degrees of freedom. For contrast analyses the voiced condition served as the baseline, and the whispered and mouthed conditions were individually compared against this baseline. The data from participants F9 and M3 were removed from statistical analysis due to tracking errors during data collection. The data from participant M1 were removed for all mouthed conditions, and the data from participants M2 and M7 were removed from word-level mouthed conditions due to lack of reliable landmarks for segmentation for these speakers. Because of the large number of variables in this study, the data will be reported primarily in tables. Data tables will include descriptive statistics across experimental conditions and summaries of repeated measures ANOVA results.

Sentence Metrics

Sentence duration. The ANOVA revealed a significant main effect for sentence duration across the speaking conditions, $F(1.225, 18.370) = 175.386$, $p = <.001$, $\eta_p^2 = 0.921$. The significant difference was found between the voiced and mouthed conditions, $F(1, 15) = 209.709$, $p = <.001$, $\eta_p^2 = 0.930$, with a change for females from a mean of 2.07 seconds for the voiced condition to a mean of 3.41 seconds for the mouthed condition. Males experienced a similar increase in duration with 1.98 seconds mean for the voiced condition and 3.28 seconds mean for the mouthed condition. The change between the voiced and whispered condition was not significant for either male or female participants, $F(1, 15) = 1.95$, $p = 0.183$, $\eta_p^2 = 0.183$.

Stroke count. The descriptive statistics can be found in Table 2 and the repeated measures ANOVA results in Table 3. There was a significant main effect for all five sensors. The whispered condition contrast revealed significant increases in stroke count for TF, LL, and UL. For the mouthed condition, there was a dramatic increase in the number of articulatory strokes in the sentence for all articulators.

Peak speed. The descriptive statistics can be found in Table 4 and the repeated measures ANOVA results in Table 5. There was a significant main effect for all five sensors. For the whispered condition a slight decline in peak speed was observed for the TM, TF, and J while the lips demonstrate no change between voiced and whispered conditions. When comparing the mouthed against the voiced conditions, there was a highly significant decline in peak speed for all five articulators.

Stroke distance. The descriptive statistics can be found in Table 6 and the repeated measures ANOVA results in Table 7. There was a significant main effect for all five sensors. Only TF and J demonstrated a decrease in distance moved for the whispered condition with no significant change from voiced to whispered for TM, LL, and UL. The stroke distance for all articulators in the mouthed condition dramatically declined compared to the voiced condition.

Stroke duration. The descriptive statistics can be found in Table 8 and the repeated measures ANOVA results in Table 9. There was a significant main effect for TM, J, and UL. For the TM there was an increase in duration between the voiced and whispered condition but no significant change for the mouthed condition. The TF had no significant change for the whispered condition but demonstrated a significant increase in duration for the mouthed condition. There was a significant increase in duration for J within both the whispered and mouthed condition when compared to voiced speech. The lip sensors showed no change in duration for the whispered condition but the LL significantly increased and UL significantly decreased for the mouthed condition.

Hull volume. The descriptive statistics can be found in Table 10 and the repeated measures ANOVA results in Table 11. There was a significant main effect for TM, TF, and UL. A significant decrease in articulatory working space, as reflected by hull volume, is present for TM and TF while the UL displayed a significant increase in hull volume in the whispered and mouthed conditions when compared to the voiced condition.

Gender effects. The gender interactions can be found in Table 12 and the gender main effects in Table 13, which were both present for a number of the variables. Gender interactions were found in stroke count for TF, stroke count for LL, and hull volume for TM. In the stroke count for sensor TF, the males demonstrated greater increases in stroke count from voiced to whispered to mouthed conditions compared to the female participants. For the LL stroke count measure, the same large increases for males compared females were observed. The females demonstrated a constant decline in hull volume for TM from voiced to whispered and then a continued decrease to the mouthed condition. Males declined from the voiced to the whispered condition but then increased in hull volume for TM again for the mouthed condition.

Two gender main effects were present in the stroke count measure for TF and LL. In both cases the stroke count for males was higher than the stroke count for females. For the LL, the peak speed was greater for females when compared to males in all speaking conditions. Males showed greater variation in peak speed throughout the conditions than female participants.

Stroke distance for LL also showed a gender main effect. Females presented with greater stroke distance throughout the study when compared to the mean stroke distance for male participants. Female participants also showed greater fluctuation in mean stroke distance than males. The TF sensor for stroke duration demonstrated longer stroke duration for the female participants when compared to males across speech conditions. Male participants also presented with shorter stroke duration in all conditions for LL when compared to the females. Female participants presented with a much smaller hull volume for LL when compared to the male participants.

Table 2

Descriptive Statistics for Stroke Count Across the Experimental Conditions by Gender

		Stroke Count						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	18.4	2.7	18.9	2.0	37.0	5.4	9.0
	Male	19.4	1.7	19.8	1.9	36.6	2.4	8.0
TF	Female	19.1	2.1	20.9	1.1	32.7	3.9	9.0
	Male	20.5	2.1	22.4	1.3	37.3	2.3	8.0
J	Female	20.7	2.9	21.3	1.5	34.9	4.7	9.0
	Male	22.1	1.9	22.8	1.2	39.0	3.6	8.0
LL	Female	19.3	3.3	20.6	1.6	33.5	4.9	9.0
	Male	21.1	1.2	22.7	1.0	39.1	2.3	8.0
UL	Female	22.6	2.3	24.9	2.0	42.6	5.5	9.0
	Male	23.1	2.3	25.3	2.1	46.8	3.8	8.0

Table 3

Repeated Measures ANOVA Results for the Number of Articulatory Strokes in the Sentence

	Stroke Count											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensors	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	1.579, 23.691	273.051	<.001	0.948	1, 15	0.741	0.403	0.047	1, 15	349.769	<.001	0.959
TF	2, 30	350.142	<.001	0.959	1, 15	15.152	0.001	0.503	1, 15	612.776	<.001	0.976
J	1.409, 21.140	231.153	<.001	0.939	1, 15	2.496	0.135	0.143	1, 15	236.974	<.001	0.940
LL	1.704, 25.567	315.588	<.001	0.955	1, 15	8.967	0.009	0.374	1, 15	491.939	<.001	0.970
UL	2, 30	305.713	<.001	0.953	1, 15	9.409	0.008	0.385	1, 15	346.154	<.001	0.958

Table 4

Descriptive Statistics for Mean Stroke Peak Speed Across the Experimental Conditions by Gender

		Peak Speed (mm/s)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	60.2	10.5	55.1	7.5	32.3	7.8	9
	Male	67.8	13.8	61.4	12.7	40.7	11.4	8
TF	Female	72.1	14.5	70.6	13.2	45.0	10.3	9
	Male	90.0	22.2	79.7	22.4	53.7	20.1	8
J	Female	36.9	9.6	40.4	9.2	27.6	8.6	9
	Male	32.4	7.7	35.2	8.2	26.2	7.8	8
LL	Female	69.7	17.5	70.9	14.5	48.0	10.9	9
	Male	53.7	12.7	55.9	14.5	39.0	10.4	8
UL	Female	25.2	6.1	24.0	6.3	18.3	6.7	9
	Male	24.7	7.2	24.0	9.4	16.2	5.7	8

Table 5

Repeated Measures ANOVA Results for the Mean Peak Speed of all Strokes in the Sentence

	Peak Speed											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 30	151.729	<.001	0.910	1, 15	15.497	0.001	0.508	1, 15	192.260	<.001	0.928
TF	1.682, 25.230	66.789	<.001	0.817	1, 15	8.274	0.012	0.355	1, 15	76.412	<.001	0.836
J	2, 30	31.987	<.001	0.681	1, 15	5.966	0.027	0.285	1, 15	34.546	<.001	0.697
LL	2, 30	37.760	<.001	0.716	1, 15	0.603	0.449	0.039	1, 15	41.889	<.001	0.736
UL	2, 30	26.937	<.001	0.642	1, 15	1.547	0.233	0.093	1, 15	40.744	<.001	0.731

Table 6

Descriptive Statistics for Mean Stroke Distance Across the Experimental Conditions by Gender

		Stroke Distance (mm)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	4.8	0.8	4.7	0.8	2.6	0.6	9
	Male	5.4	1.2	4.9	0.9	3.4	1.0	8
TF	Female	5.5	1.1	5.3	1.0	3.7	0.8	9
	Male	6.3	1.5	5.8	1.5	4.2	1.5	8
J	Female	2.7	0.8	3.0	0.8	2.3	0.8	9
	Male	2.3	0.7	2.5	0.6	2.1	0.8	8
LL	Female	5.0	1.4	5.2	1.2	3.9	1.0	9
	Male	3.6	0.8	3.7	1.0	3.0	0.9	8
UL	Female	1.7	0.4	1.7	0.5	1.3	0.5	9
	Male	1.7	0.6	1.7	0.7	1.1	0.4	8

Table 7

Repeated Measures ANOVA Results for the Mean Distance of all Strokes in the Sentence

	Stoke Distance											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 30	100.080	<.001	0.870	1, 15	2.708	0.121	0.153	1, 15	154.952	<.001	0.912
TF	1.706, 25.597	46.745	<.001	0.757	1, 15	7.021	0.018	0.319	1, 15	57.966	<.001	0.794
J	2, 30	8.689	0.001	0.367	1, 15	5.707	0.030	0.276	1, 15	5.145	0.039	0.255
LL	2, 30	13.434	<.001	0.472	1, 15	0.615	0.445	0.039	1, 15	14.617	0.002	0.494
UL	2, 30	22.521	<.001	0.600	1, 15	0.271	0.610	0.018	1, 15	35.092	<.001	0.701

Table 8

Descriptive Statistics for Mean Stroke Duration Across the Experimental Conditions by Gender

		Stroke Duration (ms)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	117.2	13.7	124.2	14.5	109.5	11.2	9
	Male	115.2	10.1	123.0	10.2	115.2	7.0	8
TF	Female	113.2	7.5	112.5	4.5	120.0	10.4	9
	Male	108.2	9.2	107.7	5.8	110.5	7.7	8
J	Female	102.3	5.3	109.5	7.7	112.9	12.8	9
	Male	98.3	9.8	102.7	6.5	106.8	9.8	8
LL	Female	111.6	11.0	112.9	8.4	118.7	14.8	9
	Male	103.8	5.4	102.9	5.7	106.6	7.0	8
UL	Female	96.4	4.5	97.0	7.5	93.2	7.8	9
	Male	97.8	8.8	96.1	7.0	90.5	5.9	8

Table 9

Repeated Measures ANOVA Results for the Mean Duration of all Strokes in the Sentence

	Stroke Duration											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 30	11.299	<.001	0.430	1, 15	10.461	0.006	0.411	1, 15	3.258	0.091	0.178
TF	2, 30	3.274	0.052	0.179	1, 15	0.089	0.770	0.006	1, 15	5.186	0.038	0.257
J	2, 30	7.593	0.002	0.336	1, 15	12.026	0.003	0.445	1, 15	10.231	0.006	0.405
LL	2, 30	2.797	0.077	0.157	1, 15	0.006	0.938	0.000	1, 15	4.982	0.041	0.249
UL	2, 30	6.095	0.006	0.289	1, 15	0.091	0.767	0.006	1, 15	9.570	0.007	0.390

Table 10

Descriptive Statistics for Sentence Hull Volume Across the Experimental Conditions by Gender

		Hull Volume (mm^2)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	104.0	29.6	86.0	21.2	68.2	21.7	9
	Male	113.4	39.4	97.1	31.6	107.1	47.7	8
TF	Female	135.8	33.6	119.7	27.0	91.1	24.3	9
	Male	185.7	65.4	165.3	62.0	168.4	93.4	8
J	Female	17.3	8.2	16.8	6.5	16.4	14.4	9
	Male	16.1	8.6	15.5	8.8	16.5	13.5	8
LL	Female	51.7	15.4	53.1	15.4	61.4	30.2	9
	Male	35.7	14.8	34.0	17.0	36.3	19.0	8
UL	Female	13.6	6.7	17.3	9.7	21.2	14.2	9
	Male	11.9	5.0	13.7	10.3	17.3	11.0	8

Table 11

Repeated Measures ANOVA Results for the Hull Volume in the Sentence

	Hull Volume											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 30	8.941	0.001	0.373	1, 15	12.941	0.003	0.463	1, 15	11.059	0.005	0.424
TF	1.41, 21.151	4.239	0.040	0.220	1, 15	8.160	0.012	0.352	1, 15	4.983	0.041	0.249
J	1.411, 21.161	0.046	0.904	0.003	1, 15	0.392	0.541	0.025	1, 15	0.009	0.925	0.001
LL	2, 30	1.009	0.376	0.063	1, 15	0.003	0.955	0.000	1, 15	1.293	0.273	0.079
UL	2, 30	7.575	0.002	0.336	1, 15	4.716	0.046	0.239	1, 15	10.461	0.006	0.411

Table 12

Gender Interactions Across the Experimental Conditions

	Gender Interactions											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Category	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
Stoke Count TF	2, 30	4.215	0.024	0.219	1, 15	0.000	0.984	0.000	1, 15	6.635	0.021	0.307
Stroke Count LL	1.704, 25.567	4.498	0.026	0.231	1, 15	0.144	0.709	0.010	1, 15	7.045	0.018	0.320
Hull Volume TM	2, 30	4.873	0.015	0.245	1, 15	0.031	0.862	0.002	1, 15	5.404	0.035	0.265

Table 13

Gender Main Effects Across the Experimental Conditions

Category	Gender Main Effects			
	df	*F*	*p*	ES
Stoke Count TF	1, 15	8.357	0.011	0.358
Stroke Count LL	1, 15	8.270	0.012	0.355
Peak Speed LL	1, 15	4.975	0.041	0.249
Distance LL	1, 15	7.081	0.018	0.321
Stroke Duration TF	1, 15	5.238	0.037	0.259
Stroke Duration LL	1, 15	7.243	0.017	0.326
Hull Volume TF	1, 15	5.833	0.029	0.280
Hull Volume L	1, 15	6.093	0.026	0.289

Word Metrics

Peak time. The descriptive statistics can be found in Table 14 and the repeated measures ANOVA results in Table 15. There was no significant main effect for all five sensors across the conditions.

Peak velocity. The descriptive statistics can be found in Table 16 and the repeated measures ANOVA results in Table 17. There was a significant main effect for all five articulators. There was no significant change in the whispered condition but all sensors revealed significant decreases in peak velocity in the mouthed condition.

Hull volume. The descriptive statistics can be found in Table 18 and the repeated measures ANOVA results in Table 19. Hull volume did not change across the conditions at the word level.

Articulator correlation. The correlation between the following articulator sets were investigated at the word level: J/TM, J/TF, TM/TF, J/LL, and UL/LL. There was no significant main effect for all five sensors across all conditions. The descriptive statistics can be found in Table 20 and the repeated measures ANOVA results in Table 21.

Table 14

Descriptive Statistics for Mean Stroke Peak Time Across the Experimental Conditions by Gender

		Peak Time (proportion)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	0.573	0.148	0.571	0.105	0.573	0.143	9
	Male	0.604	0.071	0.608	0.099	0.621	0.073	6
TF	Female	0.735	0.043	0.723	0.060	0.759	0.038	9
	Male	0.780	0.030	0.773	0.029	0.787	0.044	6
J	Female	0.739	0.045	0.730	0.047	0.735	0.047	9
	Male	0.760	0.058	0.789	0.041	0.753	0.039	6
LL	Female	0.733	0.044	0.730	0.043	0.725	0.041	9
	Male	0.745	0.062	0.756	0.057	0.753	0.052	6
UL	Female	0.644	0.077	0.612	0.114	0.578	0.113	9
	Male	0.679	0.066	0.695	0.056	0.676	0.035	6

Table 15

Repeated Measures ANOVA Results for the Mean Peak Time of all Strokes in the Word

	Peak Time											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensors	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 26	0.075	0.928	0.006	1, 13	0.003	0.955	0.000	1, 13	0.109	0.746	0.008
TF	1.637, 21.278	1.591	0.227	0.109	1, 13	0.973	0.342	0.070	1, 13	1.272	0.280	0.089
J	2, 26	0.809	0.456	0.059	1, 13	1.328	0.270	0.093	1, 13	0.151	0.704	0.011
LL	1.664, 21.630	0.062	0.913	0.005	1, 13	0.233	0.638	0.018	1, 13	0.000	0.993	0.000
UL	2, 26	1.683	0.205	0.115	1, 13	0.198	0.664	0.015	1, 13	3.862	0.071	0.229

Table 16

Descriptive Statistics for Mean Stroke Peak Velocity Across the Experimental Conditions by Gender

		Peak Velocity (mm/s)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	103.3	37.6	104.3	33.0	74.1	31.4	9
	Male	99.4	22.1	102.4	14.2	71.1	30.8	6
TF	Female	148.8	45.5	145.0	41.4	115.4	32.8	9
	Male	172.4	51.0	170.3	52.6	131.0	36.7	6
J	Female	86.1	26.7	85.2	24.6	66.9	24.3	9
	Male	70.4	21.5	71.1	19.9	62.0	27.9	6
LL	Female	182.5	54.6	185.6	51.7	143.7	45.3	9
	Male	155.5	36.3	148.2	26.2	116.9	42.4	6
UL	Female	-55.5	20.0	-58.1	22.3	-42.3	17.2	9
	Male	-56.8	15.8	-59.3	21.9	-39.3	14.2	6

Table 17

Repeated Measures ANOVA Results for the Mean Peak Velocity of all Strokes in the Word

	Peak Velocity											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 26	17.216	<.001	0.570	1, 13	0.231	0.639	0.017	1, 13	17.561	0.001	0.575
TF	1.671, 21.719	9.510	0.002	0.422	1, 13	0.267	0.614	0.020	1, 13	11.897	0.004	0.478
J	2, 26	4.632	0.019	0.263	1, 13	0.001	0.974	0.000	1, 13	6.897	0.021	0.347
LL	2, 26	12.465	<.001	0.490	1, 13	0.075	0.788	0.006	1, 13	20.728	0.001	0.615
UL	2, 26	20.278	<.001	0.609	1, 13	0.981	0.340	0.070	1, 13	23.780	<.001	0.647

Table 18

Descriptive Statistics for Word Hull Volume Across the Experimental Conditions by Gender

		Hull Volume (mm^2)						
		Voiced		Whispered		Mouthed		N
Sensor	Gender	M	SD	M	SD	M	SD	
TM	Female	19.0	12.9	20.3	16.3	12.9	7.2	9
	Male	18.9	11.6	19.4	9.8	18.8	9.5	6
TF	Female	20.4	17.8	20.0	13.3	18.7	10.3	9
	Male	21.3	9.0	24.3	10.5	35.0	23.3	6
J	Female	4.7	2.7	5.3	3.6	6.7	8.6	9
	Male	4.9	5.9	5.0	4.2	4.7	3.1	6
LL	Female	11.9	4.9	15.3	7.6	18.2	15.9	9
	Male	11.7	12.4	10.3	9.1	7.2	5.5	6
UL	Female	4.0	2.9	4.2	2.7	5.1	5.1	9
	Male	2.7	2.7	3.1	2.9	2.6	2.1	6

Table 19

Repeated Measures ANOVA Results for the Hull Volume in the Word

	Hull Volume											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2, 26	1.423	0.259	0.099	1, 13	0.286	0.602	0.022	1, 13	1.199	0.293	0.084
TF	1.414, 18.379	1.519	0.242	0.105	1, 13	0.518	0.484	0.038	1, 13	1.776	0.206	0.120
J	1.354, 17.602	0.243	0.700	0.018	1, 13	0.349	0.565	0.026	1, 13	0.363	0.557	0.027
LL	1.464, 19.027	0.073	0.877	0.006	1, 13	0.427	0.525	0.032	1, 13	0.083	0.777	0.006
UL	1.274, 16.556	0.289	0.654	0.022	1, 13	1.247	0.284	0.088	1, 13	0.457	0.511	0.034

Table 20

Descriptive Statistics for Correlations Between Articulators Across the Experimental Conditions by Gender

		Correlations						
		Voiced		Whispered		Mouthed		N
Sensors	Gender	M	SD	M	SD	M	SD	
J-T3	Female	0.172	0.453	0.209	0.474	0.344	0.486	9
	Male	0.305	0.521	0.209	0.510	0.437	0.300	6
J-T4	Female	0.839	0.141	0.850	0.164	0.900	0.123	9
	Male	0.865	0.127	0.856	0.082	0.909	0.063	6
T3-T4	Female	0.600	0.249	0.606	0.240	0.591	0.301	9
	Male	0.628	0.392	0.586	0.377	0.635	0.248	6
J-LL	Female	0.858	0.103	0.885	0.084	0.857	0.102	9
	Male	0.845	0.126	0.873	0.069	0.895	0.063	6
UL-LL	Female	-0.454	0.145	-0.365	0.183	-0.429	0.188	9
	Male	-0.400	0.243	-0.396	0.211	-0.376	0.137	6

Table 21

Repeated Measures ANOVA Results for the Correlations Between Articulators in the Word

	Correlations											
	Main ANOVA				Whispered Contrast				Mouthed Contrast			
Sensors	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
J-T3	1.677, 21.801	2.271	0.134	0.149	1, 13	0.162	0.694	0.694	1, 13	3.754	0.075	0.224
J-T4	2, 26	2.320	0.118	0.151	1, 13	0.004	0.949	0	1, 13	2.554	0.134	0.164
T3-T4	1.526, 19.842	0.063	0.896	0.005	1, 13	0.232	0.638	0.018	1, 13	0.001	0.981	0
J-LL	2, 26	1.712	0.200	0.116	1, 13	2.985	0.108	0.187	1, 13	2.791	0.119	0.177
UL-LL	2, 26	0.597	0.558	0.044	1, 13	2.274	0.156	0.149	1, 13	0.234	0.637	0.018

Discussion

Data analysis revealed that overall there were more significant changes between the voiced and mouthed conditions for all articulators at the sentence level. The contrasts showed there were significant changes for all articulators in the mouthed condition at the sentence level in the following categories: stroke count, peak speed, and stroke distance. All articulators but the TM showed significant change for stroke duration under the mouthed condition. Hull volume also decreased significantly for all but the J and LL. The sentence level measures were more sensitive to change across conditions than the word level metrics. However, peak velocity did show a significant decrease for all sensors at the word level in the mouthed condition.

Sentence Metrics

Sentence duration. Between the voiced and whispered conditions, sentence duration did not significantly change for males or females. There was a dramatic change observed by the experimenters during data collection and statistically demonstrated between the voiced and mouthed conditions. This change could be related to the significant increase in the number of strokes for the mouthed condition when compared to the voiced condition for all articulators. As well as additional strokes, the mouthed condition also resulted in increased stroke duration for the majority of articulators with the exception of the UL and TM.

Adams et al. (1993) conducted a study in which the effect of varied speech rates on velocity profiles for two articulators was examined. The study found that slower speaking rates produced multiple velocity peaks with asymmetrical patterns, while a quicker speech rate resulted in a single velocity peak and symmetrical pattern for a single articulatory gesture. Similar results were found in the present study, with the movement patterns associated by Adams et al. (1993) with a faster speech rate being equivalent to the voiced condition, and the slower speech rate (with multiple velocity peaks) being comparable to the mouthed condition. Increased duration in the mouthed conditions was also associated with increased stroke count and decreased peak velocity. We speculate, as did Adams and his colleagues, that in the unfamiliar mouthed condition there may be a shift in the speech motor control strategy, and multiple sub-movements may contribute to an articulatory gesture, whereas in the voiced condition, a single gesture is used to produce the same movement. The voiced condition in the current study is a familiar style that is used on a daily basis by all participants. When this is compared to the unfamiliar nature of the mouthed condition, significant changes are observed. These changes may be linked to the need for increased self-monitoring, especially for complex and precise articulatory movements, which is not necessary in the voiced condition.

Stroke count. A significant main effect for all five sensors was found across conditions. It could be speculated that the TF, LL, and UL increased in stroke count for the whispered condition because of the decrease in auditory feedback and increased need to rely on tactile feedback for precise articulatory placement. When all auditory feedback and laryngeal support are removed in the mouthed condition, stroke count dramatically increased for each articulator, which may reflect decreased smoothness in articulatory movements, as discussed in the previous section.

Peak speed. The most significant change was found between the voiced and mouthed conditions with a strong decline in the mean peak speed of a stroke. This once again could support the speculation of less familiar and less skilled movements in the mouthed condition. The decrease in peak speed may be related to the increase in stroke duration and overall sentence duration. Decreased peak speed is also seen in the whispered condition for the TM, TF, and J, but lip movement was not affected.

Stroke distance. Stroke distance significantly declined for TF and J in the whispered condition and for all sensors in the mouthed condition when compared to the voiced condition. The decrease in stroke distance may be related to decreased articulatory reach during speech output resulting in the undershooting of targeted sound production. Decreased stroke distance in the mouthed condition may be related to the fact that there was an increased number of strokes, but the same number of phonemes in the sentence for each speaking condition. The decrease in stroke distance is also consistent with the increase in stroke count and the decrease in hull volume in the mouthed condition.

Stroke duration. There was a significant main effect for TM, J, and UL. The duration for TM and J both increased in the whispered condition while no significant change was detected in the other three articulators. All the articulators significantly increased in stroke duration for the mouthed condition. The mouthed condition is the most unaccustomed speaking condition in the current study, and this atypical behavior may have affected the precision and speed with which articulatory movements were performed. Speech relies on a complex sequence of events that may require more self-monitoring and sub-movements to complete a stroke when all auditory and laryngeal feedback is removed, which would impact the stroke duration.

Hull volume. There was a significant main effect for TM, TF, and UL in all conditions, but the hull volume for LL and J did not change across conditions. This reflects the smaller articulatory space of TM and TF for the mouthed condition due to smaller stroke distance and increased number of strokes for the same utterance. There was also a slight increase in hull volume for LL and a significant increase in hull volume for the UL during the mouthed condition, which could be related to the fact that the LL and UL provide tactile feedback to the speaker and visual information to the communication partner in a situation where the speaker may wish to convey a message without sound. This visual information may be used to increase intelligibility of speech output in the mouthed condition while the other articulators, which showed decreased hull volume, would not impact visual information or intelligibility.

Decreased hull volume for at least TM and TF may also be associated with decreased peak speed in the whispered and mouthed conditions. The smaller articulatory movement area and decreased stroke distance may have limited the peak velocity of a stroke for the mouthed condition.

Gender effects. The reason for the observed gender differences is unclear. However, there may be subtle differences in sensory feedback or motor control strategies for males compared to females. It may be possible in future research to examine these potential issues more systematically.

Word Metrics

The word metrics were not sensitive to change across the conditions with the exception of peak velocity. All articulators decreased in velocity from the voiced to mouthed condition but remained relatively the same in the whispered condition. This finding mirrors peak speed at the sentence level. Although significant change was found between the voiced and mouthed conditions in peak velocity, the word level measures still did not detect a significant change between the voiced and whispered condition, whereas this was found at the sentence level. These findings suggest that the sentence level metrics are the most sensitive and reliable way of detecting significant change within subjects across different conditions. By only studying articulatory effects at the word level, researchers may overlook significant effects that are manifest when a longer sample of speech movements is evaluated.

General Discussion

The greatest difference was found between the voiced and mouthed conditions. The voiced condition is reflective of a familiar daily experience where speech output is influenced by auditory, laryngeal, visual, and tactile feedback. Normal speech is often considered to be an overlearned task that integrates sensory feedback with little or no conscious effort. When introduced to the less accustomed mouthed condition, a speaker must make certain compensations for the lack of normal feedback. It could be speculated that in the mouthed condition, the participants relied more on tactile and visual feedback, making speech more of a self-conscious, deliberate act. In the mouthed condition, participants in the study increased lip movement, without any prompting, demonstrating a compensatory strategy of increased sensory feedback not only for the speaker but also to potentially increase intelligibility with a conversational partner.

The reason for the increase in sentence duration, stroke count, and stroke duration as well as the decrease of hull volume, peak velocity, and stroke distance at the sentence level in the mouthed condition may be associated with the lack of auditory and laryngeal feedback. Although we believe that both types of feedback play a role in speech output, it is unclear what proportion of each type of feedback contributed to the articulatory changes in the mouthed condition. This could be an area of further research, which is addressed below.

There were dramatic, statistically significant differences in the sentence level measures, especially between the voiced and mouthed conditions. The same differences were not detected at the word level except for peak velocity. This finding alone is important for future studies because it shows the importance of expanding experimental material to at least the sentence level. Word level metrics may not be sufficient for detecting all significant changes in articulatory movement under different speaking conditions.

Limitations of the Present Study and Direction for Future Research

The current study sample was limited to twenty participants (10 males, 10 females) ranging from early 20s to early 30s. In future studies the sample size could be increased and the age range expanded. Researchers could explore the differences in articulatory activity across conditions between children, teenagers, young adults, and elderly participants. An increased sample size would allow for significant findings to be more broadly generalized. All of our participants also lived in the Provo, Utah area and many were attending Brigham Young University. All participants spoke Standard American English with no discernible regional dialect. Future studies could draw from participants across the country and may include individuals who speak different dialects of English.

This study explored the articulatory changes across three speaking conditions within a single sentence and then narrowed the study to focus on a word within that same sentence. Future studies could explore more speaking conditions and analyze more than one sentence from each participant.

The researchers in the current study speculated that the changes between the voiced and mouthed conditions were attributable at least in part to the absence of auditory and laryngeal feedback, but there was no way from the current data set to know which had the biggest effect on the observed changes. Future studies could follow a similar format but apply masking sound as the participants are repeating sentences. Researchers could also have participants mouth sentences while using an electrolarynx, which would then provide the auditory feedback lacking in this study. The data from the mouthed condition using the electrolarynx could be compared to a controlled mouthed condition.

The NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada) was used to record articulatory movement in the x, y, and z planes. This system requires 3 mm sensor coils to be attached to the different articulators being monitored. The current study took adaptation into consideration, but it is suspected that participants may never fully adapt to the sensors, which may result in acoustic and perceptual changes. The sensors may also alter the participants' ability to use tactile feedback in the production of speech, especially for the TM and TF sensors. The current study had participants speak continuously for twenty minutes with the sensor attached before data were collected. Future studies could increase the adaptation period or change the sensor placement to be less obtrusive.

Conclusion

The current study demonstrates the coordinated activity of the larynx and vocal tract during normal speech. There was a significant change in articulatory movements between the voiced and mouthed conditions when auditory and laryngeal feedback was absent. The study also revealed the lack of sensitivity to change of several metrics computed at the word level, and the need for future studies to focus at the sentence level or above.

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APPENDIX A: ANNOTATED BIBLIOGRAPHY

Adams, S. G., Weismer, G. G., & Kent, R. D. (1993). Speaking rate and speech movement velocity profiles. *Journal of Speech and Hearing Research, 36*, 41-54. *doi*:10.1044/jshr.3601.41

Objective: The study explored the effects of altered speaking rates on a speaker's velocity profile. *Method*: Five subjects with no prior speech, language, or hearing problems participated in the study. Participants produced fifty utterances differing in speech rates throughout the data collection process. Ten sensors were affixed to different oral and facial structures. The sensors on the tongue tip and lower lip were mainly used for data analysis in this study. Researchers examined at the movements of the tongue tip and lower lip during the production of the /n/ and /b/ sounds at a variety of speech rates. *Results:* Data analysis revealed that the duration of the tongue and lower lip movements increased as the participants' speaking rate decreased. Data also revealed that velocity profiles for the faster speech rates demonstrated symmetrical and smooth velocity peaks. When producing slower speech rates, participants' velocity profiles became asymmetrical and the number of velocity peaks increased. *Conclusion*: The variability of symmetry with varying speech rates is not consistent with some motor programming theories. Recently, authors have attributed the asymmetries at slower speech rates to the ability of speakers to receive feedback at the slower rates and adjust articulatory movements throughout the production of a sound. Studies including a variety of movements throughout the body (such as hand movement) have found an increase in velocity peaks at slow rates also demonstrating that this may not just be an articulatory phenomenon. *Relevance to the current work*: In the mouthed condition of the current study, a slower speech rate was observed which could reflect similar results for velocity peaks and asymmetry data between the voiced and mouthed conditions.

Behrman, A. (2013). The production and perception of vowels. In S*peech and Voice Science* (2nd ed., pp. 218-227). San Diego, CA: Plural Publishing.

Relevance to the Current Work: The textbook addresses two main aspects of the acoustic theory of speech production. First the book discusses the movement of articulators in the production of certain speech sounds. Then more specific information concerning the source-filter theory is discussed. The characteristics of the source, fundamental frequency, and filtering by the vocal tract are also covered in depth.

Cannito, M. P., Woodson, G. E., Murry, T., & Bender, B. (2004). Perceptual analyses of Spasmodic Dysphonia before and after treatment. *Archives of Otolaryngol--Head and Neck Surgery, 130*, 1393-1399. doi: 10.1001/archotol.130.12.1393

Objective: This study investigated the effects of botulinum toxin type A (Botox) on the fluency and voice quality in persons with adductor spasmodic dysphonia (ADSD). *Method*: The participants consisted of 42 native English-speaking adults (22-79 years), who had been previously diagnosed with ADSD by an otolaryngologist and evaluated by a speech pathologist. ADSD severity level was determined by 2 speech pathologists before the injection and participants were divided into five sub-groups based on severity. Each participant received injections of Botox into just the left vocal fold or both vocal folds. Botox injections were novel for all participants in the study. During the study, participants were asked to read a passage two weeks before the Botox injection and then again two to six weeks after the injection. The data collected for each participant with ADSD was compared to a healthy control matched by age and sex. *Results*: Participants in the mild ADSD subgroup did not demonstrate significant improvement post injection, while participants within the moderate, severe, and profound subgroups demonstrated significant improvement in vocal quality and fluency. There were also minor improvements between pre- and post-injection data for the older ADSD participants. *Conclusion*: Botox injections into left or both vocal folds of persons with ADSD led to significant improvement in voice quality and fluency. Minimal improvements were noted with older participants and those with mild ADSD, but these were not statistically significant. Botox injections had the most effect on persons diagnosed with profound ADSD. *Relevance to the current work:* Participants' articulation (fluency) was affected while only the larynx was targeted during treatment, indicating that changes to the larynx can influence the activity of the supraglottic articulators.

Caruso, A. J., Abbs, J. H., & Gracco, V. L. (1988). Kinematic analysis of multiple movement coordination during speech in stutterers. *Brain, 111*, 439-456. doi: 10.1093/brain/111.2.439

Objective: The study explored the connection between stuttering and an impairment in the neuromotor coordination of the upper lip (UL), lower lip (LL), and jaw (J). *Method*: Twelve adult stutterers participated in the study. Subjects were instructed to repeat the word "sapapple" which was chosen because of the articulator coordination necessary to produce the word. The stutterers' fluent repetitions were used for analysis. The data collected from the stuttering group were compared to a control group of normal speakers. *Results*: Data collected demonstrated slight differences in the movement of UL, LL, and J of adult stutterers compared to normal speakers. When the movements of the UL, LL, and J were combined, the difference was found to be insignificant. The 2,000 utterances produced by the stuttering group showed that stutterers are capable of producing smooth single-peaked velocity profiles, the same as normal speakers. The authors also examined the movement sequencing of the articulators. Normal speakers showed consistency in the movement of the UL, LL, and J when producing "sapapple." This same consistent sequencing was not observed in the stuttering subjects. Data also showed that the onset of articulatory movements for stutterers was delayed compared to normal subjects. *Conclusion*: This study concluded that people who stutter are capable of producing speech smoothly, as revealed by the single-peaked velocity profiles. Even with smooth production, the study also demonstrated the difference in articulatory sequencing that is not present in normal speaker. This change in sequencing may suggest some level of neurological impairment in stutterers. *Relevance to the current work:* This study discusses the coordination between articulators and necessary sequencing patterns to produce speech. The sequencing patterns of articulators during different speaking conditions will be explored further in the present study.

Cookman, S., & Verdolini, K. (1999). Interrelation of mandibular laryngeal functions. *Journal of Voice, 13*, 11-24.

Objective: This study investigated the connection between laryngeal adduction and movement of the jaw. Method: Twelve normal adults with no history of voice disorder or voice training participated in this study. Each participant sustained a vowel for 4 seconds in 12 different speaking conditions. The following three variables were adjusted: jaw opening (10 mm, 25 mm, 40 mm), jaw biting pressure (10 kPa, 200 kPa), and fundamental frequency (conversational, high-pitch). Participants' laryngeal movement (adduction and abduction) was determined throughout each condition using an electroglottograph (EGG). Results: Fundamental frequency at the conversational level was associated with increased laryngeal adduction compared to the high-pitch condition throughout the study. In the conversational condition, analysis of data revealed the highest laryngeal adduction for both genders when the jaw was opened to 40 mm. For males, the 200 kPa biting pressure yielded increased laryngeal adduction. For females, there was hardly any difference between the two jaw biting pressures. In the high-pitch condition, data revealed that males showed greater laryngeal adduction than females. Males also demonstrated greater adduction at small and medium jaw openings compared to the larger opening. Female participants also presented with higher levels of adduction for the 10 kPa pressure than the 200 kPa pressure in the high-pitch condition. Conclusion: The most significant discovery made through this study was that when the fundamental frequency was at the conversational level, adduction increased when the jaw was dropped for both genders. Clinical experience suggests that dropping the jaw can help with the reduction of laryngeal hyperfunction, but according to this study, adduction can actually increase when the jaw is in the dropped position. For males, relaxation of the jaw in conversational pitch conditions may be the better option when trying to decrease hyperfunction. The effects of jaw manipulation on laryngeal movement in the high-pitch condition were not conclusive in this study. Relevance to the current work: This study showed a direct relationship between jaw manipulations and laryngeal adduction.

Dromey, C. (2010). Laryngeal articulatory coupling in three speech disorders. In P.Van Lieshout, B. Maasen, & H. Terband (Eds.), *Speech motor control: New developments in basic and applied research* (pp. 283-296). Oxford: Oxford University Press. doi: 10.1093/acprof:oso/9780199235797.001.0001

Relevance to the Current Work: This chapter explores the relationship between the articulators and larynx in the following three disorders: Parkinson's disease (PD), spasmodic dysphonia (SD), and muscle tension dysphonia (MTD). Patients with PD participated in Lee Silverman Voice Treatment (LSVT), which addresses respiratory support while encouraging louder speech. Along with laryngeal changes, there were also changes in articulation and prosody. Patients with SD temporarily addressed laryngeal problems with Botox injections into the thyroarytenoid muscle. After Botox injections, laryngeal and articulatory improvements were observed. MTD therapy is focused on decreasing tension in the larynx through circumlaryngeal massage or repositioning techniques. Even though the larynx is the focus of MTD therapy, a study discussed in this chapter found that articulatory movement was also improved.

Dromey, C., Nissen, S. L., Roy, N., & Merrill, R. M. (2008). Articulatory changes following treatment of Muscle Tension Dysphonia: Preliminary acoustic evidence. *Journal of Speech, Language, and Hearing Research, 51*, 196-208. doi: 10.1044/1092-4388(2008/015)

Objective: Treatment for muscle tension dysphonia (MTD), such as circumlaryngeal massage, has proven effective in reducing the effects of MTD on vocal quality but this study investigated the effects of MTD treatment on articulatory activity as well. *Method*: Pre- and post-recordings of 111 women who had previously been diagnosed and received treatment (manual circumlaryngeal techniques) for MTD were analyzed for evidence of significant change between the two recordings. For each recording (pre and post), the participants were instructed to read two sentences from *The Rainbow Passage*. These recordings were then analyzed for temporal, acoustic, and perceptual changes. Data were also compared to a control group of 20 women who were recorded repeating the same two sentences twice at similar recording intervals. This comparison was mainly used to address the issue of practice effects. *Results*: Each participant with MTD demonstrated improved vocal quality after one voice therapy session. Analysis of the data revealed significant changes in perceptual severity; speaking time ratio; F1 and F2 slope; and F1 and F2 transition extent for the MTD group. Data also revealed a correlation between the MTD severity ratings received and certain formant transition slopes and extents as well as sample duration and speaking time ratio. *Conclusion*: The study showed a significant perceptual difference between pre- and post-treatment recordings for patients with MTD. Changes of equal significance were not observed within the control group. Along with finding vocal quality changes, the authors also found that participants with MTD demonstrated significant articulatory acoustic changes. Specific changes include increased F2 slope in diphthong production and decreased duration. *Relevance to the current work*: The study demonstrated how focused treatment to laryngeal structures would not only affect perceptual outcomes but also improve articulatory movements.

Dromey, C., Ramig, L. O., & Johnson, A. B. (1995). Phonatory and articulatory changes associated with increased vocal intensity in Parkinson disease: A case study. *Journal of Speech and Hearing Research, 38*, 751-764. doi: 10.1044/jshr.3804.751
Objective: This case study explored speech and voice changes in a patient with Parkinson Disease (PD) when only vocal intensity was addressed. *Method*: One participant was chosen from a larger group of patients diagnosed with PD. The participant chosen for this case study was a male, 49-years-old, family physician, and in the early stages of PD. The participant was asked to perform seven tasks centered on phonatory and articulatory abilities. Tasks were recorded two weeks prior to vocal intensity treatment, two weeks post-treatment, six months post-treatment, and twelve months post. Data were analyzed using laryngeal, respiratory, and articulatory acoustic measures. The participant received four weeks (16 sessions) of Lee Silverman Voice Treatment (vocal intensity treatment). *Results*: Sound pressure level (SPL) in sustained vowel phonation demonstrated the most significant improvement throughout the study when compared to syllable series, reading, and monologue. Increased SPL was maintained through the 12 months of data collection. Subglottal pressure, laryngeal airway resistance, and maximum flow declination rate all increased throughout the treatment and remained above pre-treatment levels at the 12-month follow-up. After treatment, the participant presented with a posterior gap between the vocal folds, which was an improvement to the bowing of his vocal folds found at pre-treatment. Vowel duration increased and remained above pre-treatment levels at the 12-month recording, but word duration decreased below pre-treatment levels. Frication duration and rise time also decreased after treatment. *Conclusion*: Post-treatment data revealed changes in phonation and articulation measures when only vocal intensity was targeted in treatment. The participant demonstrated an increase in phonatory control and strength and also increased coordination between oral articulators and the larynx. *Relevance to the current work*: Treatment focusing solely on the larynx and increasing vocal intensity resulted in improved articulatory and speech coordination.

Dromey, C., Reese, A., & Howey, S. (2007). Lip kinematics in Spasmodic Dysphonia before and after treatment with Botulinum toxin. *Journal of Medical Speech-Language Pathology, 15*, 263-277.
Objective: Articulatory movements were analyzed in patients with Spasmodic Dysphonia (SD) before and after receiving injections of Botulinum Toxin (Botox) as a form of treatment. *Method*: Seven adults (4 females, 3 males) who had previously been diagnosed with adductor SD volunteered as participants for this study. There was also a control group that consisted of three

adult participants (2 females, 1 male). The adults within the SD group each participated in two different recording sessions, which were held one week before the Botox injections and then 4 to 6 weeks after. During each recording session, participants were instructed to say the following sentence: *Buy Bobby a puppy*. Participants were recorded repeating the sentence 15 times in a normal voice and then 15 times in the whispered condition. Adults in the control group were also recorded. Aerodynamic data were also collected by having the participants produce the /pa/ syllable five time on one breath. *Results*: In pre-treatment analysis, researchers found a decreased duration during the whispered condition. Both behaviors (normal voice and whisper) in post-treatment data revealed shorter duration. Displacement and velocity measures also decreased for the SD group in post-treatment data for bilabial closure. Correlation between the upper lip and lower lip also improved with the Botox treatment for the participants with SD. The velocity peak counts for the SD group also improved and became more similar to profiles seen in the control group in after treatment data. Perturbation for the participants with SD was reduced by almost 50% with Botox treatment and vocal quality was rated higher perceptually. *Conclusion*: Although the sample was small, this study showed the effects of Botox injection treatment on patients with adductor SD. The pre- and post-treatment recordings showed the effects the treatment can have on laryngeal deviations such as jitter and shimmer. Data also revealed the beneficial gains in vocal quality during post-treatment analysis. As well as laryngeal changes, improvements in articulatory kinematic measures were observed. *Relevance to the current work*: This study revealed laryngeal and articulatory gains that come from treatment focused solely on improving laryngeal function.

Gracco, V. L. (1988). Timing factors in the coordination of speech movements. *The Journal of Neuroscience, 8*, 4628-4639.

Objective: The study examined the specific articulatory movements and muscle timing necessary for labial opening compared to labial closure. *Method*: Two males and two females participated in the study. Orofacial muscle (2 upper lip depressors and 2 lower lip elevators) activity was observed while subjects repeated the word *sapapple* 70-150 times each. *Results*: Previous labial closure studies showed a sequenced pattern of upper lip, lower lip, and then jaw with very few variations. This same consistency was not observed with labial closure when the 502 repetitions were analyzed. The analysis also revealed that even though the articulatory pattern for labial closure was consistent, the muscle movement for labial closure was more variable. Data also showed that compared to the lower lip, the upper lip had a shorter latency between muscle peak amplitude and the velocity peak. *Conclusion*: Different muscle and articulatory movements were required for labial closure versus opening. Kinematic sequencing was more consistent across subjects than muscle movement when producing speech. The author speculated that the timing of all the articulators is necessary when producing the /p/ in *sapapple* to build up adequate pressure but when producing the vowel sound, timing during labial opening is not as crucial. *Relevance to the current work:* This study investigated the coordination between the lip and jaw during speech production, which will be investigated in current study.

Gracco, V. L., & Löfqvist, A. (1994). Speech motor coordination and control: Evidence from lip, jaw, and laryngeal movements. *The Journal of Neuroscience, 14*, 6585-6597.

Objective: The study explored lip, jaw, and laryngeal movement during the production of the voiceless consonants /f/ and /p/. *Method*: Three males participated in the study. They were each asked to repeat phases that contained the /f/, /p/, or /ft/ sounds. The words included *sapapple*, *supper*, *suffer, safe, safety, sipping, and sifting.* The words were repeated forty times each throughout the study. The authors examined the articulatory coordination between the jaw, lower lip, and glottal openings. A fiberscope was used to track laryngeal movement and LEDs attached to the nose, upper lip, lower lip, and jaw were used to track articulatory movements. *Results*: The authors found that the vocal folds adducted before the jaw would lower across all three subjects. It was also found that the closing of the upper and lower lips is correlated to the adduction of the vocal folds. It was found that the relative timing of the lip, jaw, and larynx were fixed but that relative timing was more consistent when the mouth was closing than opening. The study also found that depending on the subsequent consonant, the jaw would open more widely or narrowly to produce the same vowel. *Conclusion*: The authors concluded that articulators (including the larynx) are controlled as a group instead of individually, based on the evidence of unchanging relative timing across subjects and phonetic variations. The study also showed varying articulatory movements in the production of the same sound depending on surrounding phonemes. *Relevance to the current work*: This study revealed consistent relative timing between articulators in the production of voiceless consonants. This knowledge will be used when analyzing relative timing of articulators in the current study.

Hughes, O. M., & Abbs, J. H. (1976). Labial-mandibular coordination in the production of speech: Implications for the operation of motor equivalence. *Phonetica, 33*, 199-221. doi:10.1159/000259722

Objective: This experiment studied the articulatory speech movements of the upper lip, lower lip, and jaw in connection with motor equivalence. *Method*: Six native English-speaking females participated in this study. Participants produced a phrase three times, each time with a variety of targeted di-syllable word. Phrases were repeated ten times in two different speech conditions: normal speaking rate and faster speaking rate. Upper lip, lower lip, and jaw movements were tracked throughout the speech sample using a strain gage transduction system. Displacement was measured for each articulator. *Results*: Vertical opening of the mouth showed very little variation, but lower lip and jaw displacement changed greatly when producing the same target sound. Analysis showed dependence between the movement of the lower lip and jaw, which was not seen with the upper lip. The lower lip and jaw contributed the most to the vertical opening of the mouth while the upper lip usually only contributed 1% of the vertical closure. The upper lip also showed more variability than the lower lip and jaw movement. Although it was found that in most cases the upper lip did not contribute as much as the lower lip, the upper lip did demonstrated the capability of compensating for lip closure when the lower lip has reduced displacement. It was found that changes in displacement were very small with the different speaking rates. *Conclusion*: The data clearly showed that motor equivalence is present in individuals during speech production. Subjects produced the same target utterances throughout the study by displacing lower lip, upper lip, and jaw to different extents. The amount of motor equivalence varies among subjects. *Relevance to the current work*: In the current study, motor equivalence within and between subjects will be considered when analyzing data.

Lofqvist, A., & Yoshioka, H. (1984). Intrasegmental timing: Laryngeal-oral coordination in voiceless consonant production. *Speech Communication, 3*, 279-289. doi:10.1016/0167-6393(84)90024-4

Objective: Relative timing of articulatory movements in varying laryngeal conditions was explored at the intrasegmental level. *Method*: Two adults (1 male, 1 female) participated in the study. Subjects recited prepared material ten to fifteen times with targeted nonsense words including voiceless stops and fricatives in varied stress locations. Material was read at a normal pace and then at an increased speed. Participants wore a customized artificial palate, which was used to record articulatory movements. A flexible fiberscope was also used to track laryngeal movements throughout. The authors explored the following inter-articulator timing: 1) the onset of oral constriction compared to the closure of the vocal folds, and 2) the biggest opening of the vocal folds compared to offset of oral constriction. *Results*: Data analysis revealed that stop closure duration was shorter than that of fricatives. Closure duration was also shorter in stressed and more rapid speech output. Onset of tongue and palatal contact was shorter in fricatives and was longer in stressed and slower speed conditions. In connection with relative timing, data revealed that there was not a significant change between the different stressed points and rate of speech. *Conclusion*: The results demonstrated a change in duration of onset times for the two inter-articulator timing measures, when different conditions of stress and speech rate were introduced. Although the duration changed, there was no change in relative timing between articulators when producing the dental voiceless stops and fricatives. *Relevance to the current work*: According to this study, when analyzing articulatory relative timing in the current study, there should be no change when different laryngeal behaviors (voiced, whispered, mouthed) are introduced.

Max, L., & Gracco, V. L. (2005). Coordination of oral and laryngeal movements in the perceptually fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research, 48*, 524-542. doi: 10.1044/1092-4388(2005/036)

Objective: This experiment examined the coordination between the larynx and oral cavity during fluent speech in stutterers and non-stutterers. *Method*: Twenty participants were divided into two equal groups of those who stuttered (5 mild, 4 moderate, 1 severe) and non-stutterers. Each participant produced four different target word sequences, which included a variety of consonants, vowels, diphthongs, and word boundaries. Each target was produced in four different conditions: short, intermediate, long-initial, and long-final. Upper lip, lower lip, jaw, and vocal fold movements were measured throughout all target utterances. Only data that were perceived to be fluent, with articulation accuracy, were used for analysis. *Results*: Data analysis revealed that those in the stuttering group displayed increased voice onset time (VOT) and devoicing intervals (DI) compared to the non-stuttering subjects. Results also revealed longer interval duration between onset and offset for stuttering participants compared to the control group. Between both groups, relative timing of articulatory movement when producing a bilabial stop was comparable. *Conclusion*: This study found that when analyzing fluent data from both stuttering and non-stuttering participants, the main difference was in the duration of certain articulatory movements. When producing the target phrases, both groups produced articulatory movements at relatively the same time. *Relevance to the current work*: When different speaking conditions were introduced, only changes in articulatory movement were found, with no significant changes in inter-articulatory relative timing.

Munhall, K. G., Löfqvist, A., & Kelso, J. A. (1994). Lip-larynx coordination in speech: Effects of mechanical perturbations to the lower lip. The *Journal of the Acoustical Society of America, 95*, 3605-3616. doi: 10.1121/1.409929

Objective: The coordination between lip, jaw, and larynx was explored during the application of a mechanical perturbation to an articulator during the production of a voiceless consonant. *Method*: Participants in this study were three persons with no prior communication disorders. One of the participants had been involved in a previous perturbation study but the other two participants had not. Lip, jaw, and laryngeal movements were recorded while participants repeated a nonsense phrases (/i'pip/ again) 400 times. Perturbations were introduces three times (early, mid, late) between the first vowel and voiceless consonant. *Results*: The data showed that voice onset time (VOT) increased for all participants when perturbations were presented. The closure time decreased during perturbation trials. Compensatory measures were implemented more regularly when perturbation was presented earlier on in the utterance. Perturbation trials also demonstrated longer articulatory movement durations as well as larger, faster, and longer duration for oral opening movement. Jaw movement was found to be shorter during perturbation trials. The larynx was also affected during perturbation trials, demonstrating delayed opening onset, and also increased laryngeal adduction duration. Data revealed that intraoral pressure was not affected by the perturbation. *Conclusion*: The analysis of data revealed two reactions from the larynx when perturbations were applied to a specific articulator. The larynx showed delayed glottal abduction and increased glottal adduction. This finding implies that the perturbations not only had an effect on the movements in the oral cavity but also on laryngeal movement. The VOT increased during perturbation, which may have been linked to delayed glottal abduction. This finding would once again show a connection between the larynx and oral cavity. *Relevance to the current work*: This experiment reported on the relationship between the larynx and oral cavity. When changes were made to one, effects were observed in the other.

Tasko, S. M., & Westbury, J. R. (2002). Defining and measuring speech movement events. *Journal of Speech, Language, and Hearing Research, 45*(1), 127-42. doi: 10.1044/1092-4388(2002/010)

Objective: The purpose of this article was to describe a novel way to identify and measure speech movements. Method: Recordings from 18 (nine males, nine females) speakers were chosen from a speech production database. Each recording included an oral reading sample of a 300-word passage. The Wisconsin X-ray microbeam system was used to track articulatory movement. Tracking pellets were applied to the tongue blade; tongue dorsum; lower lip; mandibular incisor, and in between the first and second molar. Kinematic records were then split into individual strokes, which are moments of acceleration followed by a moment of deceleration. Each stroke was analyzed based on distance, duration, speed, and boundary speed (which is the speed at the onset and offset). *Results*: Data analyzed from the eighteen speakers revealed an average stroke duration of 138 ms with a range from 15 ms to 500 ms. Average stroke distance was 4.7 mm with a range of near zero to more than thirty mm. The range for the peak speed of a stroke was near zero mm per second (mm/s) to 400 mm/s, while the average was 51 mm/s. The average boundary speed of a stroke ranged from near zero mm/s to 100 mm/s with an average of 12 mm/s. *Conclusion*: This approach for identifying and defining articulatory movements is appropriate for studies that use point-tracking techniques. The splitting of articulatory movements into strokes is an effective way of defining articulatory movement for later measurement. Using strokes can give insight into the distance, duration, and speed traveled by certain articulators during speech production, which can easily be compared to other conditions. *Relevance to the current work*: The concept of dividing articulatory movements into strokes was used in the current study to calculate stroke count, onset speed, peak speed, mean speed, and duration at the sentence level.

Tingley, S., & Dromey, C. (2000). Phonatory-articulatory relationships: Do speakers with spasmodic dysphonia show aberrant lip kinematic profiles? *Journal of Medical Speech-Language Pathology, 8*, 249-252.

Objective: The authors explored the effects of laryngeal spasms on articulatory movements in patients with spasmodic dysphonia. *Method*: Three adults (1 man, 2 women) diagnosed with varying severities and types of SD participated in the study. All data from the participants with SD was compared to a control participant (1 man). All participants completed the same tasks. Participants were instructed to repeat the sentence *Buy Bobby a puppy* twenty times while upper and lower lip movements were recorded. Participants repeated the sentence in the following two laryngeal conditions: voiced and whispered. The authors analyzed data from both speaking conditions for velocity profiles, displacement, and inter-articulator correlation. *Results*: Velocity profiles for the control participant and the participant with mild SD were smoother, revealing only single or double velocity peaks, while those with more severe SD (abductor and adductor) displayed multiple velocity peaks. Spatiotemporal Index (STI) was not found to be significantly higher for those with more severe SD when compared to the control subject. This means that articulatory movements made in conjunction with laryngeal spasms happened consistently across recordings. The authors also found many changes in the continuous correlation function (CCF) for those with SD compared to the control subject. *Conclusion*: The study found that those patients with more severe SD demonstrated greater articulatory movement interference than the control participant, when laryngeal spasms were present. The data from the two participants with severe SD showed greater differences compared to the control subject than the participant with mild SD. This suggests that the more severe the diagnosis of SD, the greater the impact on articulatory kinematics. *Relevance to the current work*: This study suggests that laryngeal interference will have a direct effect on articulatory movements, which shows the direct relationship between the two systems.

APPENDIX B: INFORMED CONSENT

Consent to be a Research Subject

Introduction
This research study is being conducted by Christopher Dromey, a professor in the department of Communication Disorders at Brigham Young University to determine how movements of the tongue and lips change under several conditions (voicing, whispering, silently mouthing the words). You were invited to participate because you are a native speaker of English and have no history of speech, language, or hearing disorders.

Procedures
If you agree to participate in this research study, the following will occur:

- you will be seated in a sound-treated recording booth in room 106 of the John Taylor Building
- six small sensor coils will be attached with dental adhesive to your tongue, teeth, and lips and one to the frame of eyeglasses (no corrective lenses) that you will wear
- while you speak, the researchers will record the movements of these articulators and audio record your speech
- you will read sentences from a sheet in front of you under several conditions: normal speech, whispering, and silent mouthing of the words
- the total time commitment will be less than 60 minutes

Risks/Discomforts
You may feel uncomfortable having the sensors attached with dental glue inside your mouth. These may cause you to mildly lisp on some sounds at first. For several hours after the study you may be able to feel a slight residue on your tongue, which will disappear within a day. This technology has been widely used at other research centers and no problems for the research subjects have been reported.

Benefits
There will be no direct benefits to you. It is hoped, however, that through your participation researchers may learn about the way speech articulator movements may change under different voicing conditions. This may expand our understanding of the way the brain controls speech movements in healthy individuals and could lead to further work that would help people with speech disorders.

Confidentiality
The research data will be kept in a locked laboratory on a password protected computer and only the researcher will have access to the data. At the conclusion of the study, all identifying information will be removed and the data will be kept in the researcher's locked office. Arbitrary participant codes, but no names, will be used on the computer files or paper records for this project in order to maintain confidentiality. In presentations at conferences and in publications based on this work, only group data will be reported.

<u>Compensation</u>
You will receive $10 cash for your participation; compensation will not be prorated. For BYU students, no extra credit is available.

<u>Participation</u>
Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without jeopardy to your class status, grade, or standing with the university.

<u>Questions about the Research</u>
If you have questions regarding this study, you may contact Christopher Dromey at (801) 422-6461 or dromey@byu.edu for further information.

<u>Questions about Your Rights as Research Participants</u>
If you have questions regarding your rights as a research participant contact IRB Administrator at (801) 422-1461; A-285 ASB, Brigham Young University, Provo, UT 84602; irb@byu.edu.

Statement of Consent
I have read, understood, and received a copy of the above consent and desire of my own free will to participate in this study.

Name (Printed):_________________ Signature:___________________ Date: _____________