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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

The Effect of Laryngeal Activity on the Articulatory Kinematics of /i/ and /u/

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This study examined the effects of laryngeal activity on articulation by comparing the articulatory kinematics of the /i/ and /u/ vowels produced in different speaking conditions (loud, comfortable, soft and whisper). Participants included 10 males and 10 females with no history of communication disorders. The participants read six stimulus sentences in loud, comfortable, soft and whispered conditions. An electromagnetic articulograph was used to track the articulatory movements. The experimenters selected the sentence *We do agree the loud noise is annoying* from the other utterances and the words *we do agree* were segmented from the sentence. *We do agree* was chosen because of the tongue and lip movements associated with the retracted and rounded vowels. Results reveal the soft condition generally has smaller and slower articulatory movements than the comfortable condition, whereas the whispered condition shows an increase in size and the loud condition shows the greatest increase in both size and speed compared to the comfortable condition. The increase in the size of the movements in whispered speech may be due to unfamiliarity as well as a decrease in auditory feedback that requires the speaker to rely more on tactile feedback. These findings suggest that adjusting laryngeal activity by speaking more loudly or softly influences articulation; this may be useful in treating both voice and articulation impairments.

Keywords: phonation, articulatory kinematics, loud speech, whisper

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DESCRIPTION OF THESIS STRUCTURE AND CONTENT

This thesis, The Effect of Laryngeal Activity on the Articulatory Kinematics of /i/ and /u/, uses a traditional thesis format based on requirements for submission to Brigham Young University. Appendix A includes an annotated bibliography. Appendix B contains the participant consent form used in this study.

Introduction

The source filter theory can be used to explain speech production. It describes the two major components of speech as the source (i.e., the vocal folds) and the filter (i.e., the vocal tract). Each of these components plays a unique role in producing speech. Both the source and the filter create specific acoustic features in the sounds we hear. By analyzing these acoustic features, we can make inferences about the vocal folds and the vocal tract respectively.

The sound source of voiced sounds is the vibrating vocal folds as air passes through them. The speed at which the vocal folds vibrate determines the fundamental frequency and subsequent harmonic frequencies. Therefore, acoustic analysis of the fundamental and harmonic frequencies is revealing of laryngeal activity.

The buzzing sound created by the vibrating vocal folds is then shaped and resonated into distinct speech sounds as it passes through the vocal tract. The vocal tract filters the frequency content, amplifying specific frequencies and dampening others, depending on where the sound resonates. The emphasized frequencies are called formants and distinguish vocalic sounds from each other, creating speech that is recognizable by listeners. As the lips, tongue, and jaw move to the next place of articulation the sound resonates differently, amplifying some frequencies and producing different speech sounds. These formants can be analyzed acoustically to reveal some aspects of how the articulators are moving (Behrman, 2013).

While the source is responsible for phonation and the filter is responsible for articulation, these subsystems do not act independently of one another. Research shows that the two are connected in their neural control and via biomechanical linkages, and that both subsystems influence each other. The findings of several studies will be discussed below, which demonstrate that changes to the source or the filter affect the other subsystem and that their actions are highly coordinated.

In order to understand the coordination between the source and the filter, Munhall, Löfqvist, and Kelso (1994) tracked the laryngeal responses of three participants who received unexpected lip perturbations while repeating an utterance. They found that when the lip was perturbed, laryngeal abduction was delayed and lasted longer. It also caused the abductors to adjust and resulted in differing movement velocities and displacement values compared to unperturbed movements. The results suggest that a change in the action of any of the articulators can affect the movements of the other articulators, including the larynx. This provides evidence of a strong connection in the control of the source and the filter.

Dromey, Nissen, Roy, and Merrill (2008) performed a retrospective study comparing the pre and posttreatment recordings of women with muscle tension dysphonia (MTD) and a control group. The participants with MTD received manual circumlaryngeal voice treatment, which frequently leads to a significant improvement in voice quality in as little as one therapy session. The authors speculated that treating the voice might also affect supraglottal articulation. In order to evaluate changes in articulatory movements, the authors compared formant changes in two diphthongs from the pre and posttreatment readings of *The Rainbow Passage*. The group of speakers with MTD demonstrated significant changes in the formant slopes and transition extents for both diphthongs, sample duration, speaking time ratio, and perceptual severity, whereas the control group did not show significant changes in any of the variables. Individuals who had the most improvements in voice quality after treatment tended to have a greater increase in /ɑI/ F2 slopes and transition extents, decreased sample duration, and increased speaking time ratio. These findings suggest that the improvements in laryngeal activity as a result of voice therapy also had an effect on the movements of the vocal tract. They also reveal that the dysphonia associated with MTD may be linked to lingual and/or mandibular activity in addition to vibration of the vocal folds.

Dromey, Ramig, and Johnson (1995) found that voice therapy led to improvements in both phonation and articulation in a case study of a 49-year-old man with Parkinson's disease (PD). He received Lee Silverman Voice Treatment (LSVT), a common voice therapy that targets loud speech for individuals with Parkinson's disease. Since glottal incompetence, reduced respiratory support and hypokinesia are common characteristics of Parkinson's disease, individuals with PD frequently experience reduced intelligibility, vocal intensity, articulatory accuracy, and speaking rate. By simply attempting to speak louder, an individual's respiratory system, vocal folds, and vocal tract make the appropriate adjustments to allow for more intelligible speech, which simplifies therapy and provides faster, more efficient results (Dromey, 2010). After treatment the participant presented with increased vocal intensity, phonatory stability, fundamental frequency variability, vocal fold adduction, and transition extent of the second formant. Not only do these improvements provide evidence for the efficacy of LSVT, the changes in transition duration, extent and rate of the second formant suggest that the vocal tract adjusted to the changes made by the speech sound source (Dromey et al., 1995).

Spasmodic dysphonia (SD) is another condition that is typically described as a voice disorder, but which also has signs of disordered articulation (Dromey, Reese, & Howey, 2007). Spasmodic dysphonia is characterized by laryngeal spasms that disrupt the flow of speech. Tingley and Dromey (2000) compared three individuals with various types and severity levels of SD to a male control. Their articulatory movements were tracked with a strain gauge transducer system on the upper and lower lips while they repeated a phrase multiple times in both a voiced and whispered condition. In whispered speech, the articulatory kinematic measures of those with spasmodic dysphonia were more similar to the control speaker, likely due to the absence of laryngeal spasms, which suggests that the laryngeal spasms in the voiced condition have an effect on articulation. The individuals with more severe cases of SD showed the greatest differences on the articulatory kinematic measures compared to the control participant, which indicates that the severity of vocal spasms influences the impact they have on articulation in individuals with SD. Therefore, vocal fold activity appears to influence the size and timing of the articulatory movements.

Dromey et al. (2007) found that speakers with SD had less coordination between their upper and lower lips, more lower lip velocity peaks, and different lower lip movement profiles compared to control speakers. Those with SD received botulinum toxin injections to chemically denervate the thyroarytenoid muscle and reduce the occurrence of laryngeal spasms. The results revealed fewer articulatory disturbances posttreatment, in addition to improvements in vocal function. Other studies have shown that Botox injections resulted in improved intelligibility and fluency in individuals with adductor SD, although they were still not as intelligible or fluent as control participants (Bender, Cannito, Murry, & Woodson, 2004; Cannito, Woodson, Murry, & Bender, 2004).

Differences in laryngeal activity can also be compared through various speech conditions such as soft and loud speaking voices. Vocal intensity is dependent on both respiratory drive and the tension and closure of the vocal folds (Behrman, 2013); the vocal folds therefore vibrate differently in order to produce speech at a greater intensity level. Schulman (1989) compared the movements and timing of the articulators when producing normal and loud speech. The findings revealed an association between loudness and the articulator displacement and velocity.

Although the jaw displacement was maintained during loud speech, the lips rounded and spread when producing vowels. As displacement increased so did the velocity, which resulted in shorter durations of bilabial stops, but longer durations for vowels in the loud condition. These results indicate that loud speech is not a simple amplification of the movements from normal speech, but rather a much more complex interaction, and that loudness is associated with larger displacement and higher velocities of the articulators.

Huber and Chandrasekaran (2006) found similar changes to articulation in loud speech. They aimed to examine how different types of cues to increase sound pressure level (SPL) affect speech kinematics. They found that each of the cues resulted in a similar SPL increase and that when compared with normal volumes, participants presented with larger displacement measures of the lower lip and jaw as well as less constriction of the tongue in loud speech. The upper lip movements were less variable in loud speech. Displacement measures did not vary based on the cue given to increase the SPL, but velocities did, likely due to the increased effort required to have more control. These results suggest that increasing vocal loudness does affect articulatory movement patterns, but they are not necessarily dependent on the type of cue given to elicit a louder speaking volume.

Another way to compare laryngeal activity is whispered versus phonated speech. Whispered speech clearly has a lower intensity than phonated speech since the vocal folds do not vibrate when whispering. The sound is produced from turbulence from the air flowing from the lungs and through the immobile vocal folds. The intelligibility of whispered speech is similar to that of phonated speech, but the articulators have to make adjustments in order to produce voiced and voiceless sounds distinctly without the vibrations of the vocal folds. Whispered speech produces longer durations for individual consonants and whole sentences than phonated speech

(Jovičić & Šarić, 2008). It is possible that the increase in duration may be due to increased awareness and more control required to articulate intelligible speech when whispered. There are differences in intensity based on the place and manner of the consonant being produced but the intensity of unvoiced consonants remains fairly constant in both the voiced and whispered conditions (Jovičić & Šarić, 2008). There is a decrease in auditory feedback when producing a whisper that causes the speaker to rely on tactile feedback, which may lead to articulatory movements that are smaller and less smooth (Barber, 2015). Since whispering is typically used for a very brief amount of time, to communicate a message in a quiet environment or to prevent others from hearing it, most speakers are not accustomed to speaking for a prolonged period of time with limited auditory feedback, which likely affects their articulatory performance.

The current study further investigated the interaction between the larynx and vocal tract. The movement of the articulators were tracked using NDI Wave electromagnetic articulography while producing an utterance including the /i/ and /u/ vowels in four different speech conditions: whispered, soft, normal and loud speech. Based on the previous research, we hypothesized differences in the articulatory movements for each of the speech conditions. These findings may have potential implications for both basic science and clinical intervention for both voice and articulation disorders.

Method

Participants

There were 10 male (ages 20-32, $M = 25.3$, $SD = 3.4$) and 10 female (ages 20-34, $M = 25.1$, $SD = 4.0$) participants in this study. They all spoke English as their native language and reported no history of speech, language, or hearing disorders. The participants were recruited from the Brigham Young University community via word of mouth. All the participants signed a consent form and received a $10 compensation for participating in the study. The consent form was approved by the Brigham Young University Institutional Review Board.

Equipment

Each participant sat in a single-walled sound booth for the recordings. Their utterances were recorded with a condenser microphone (AKG C2000B, Vienna, Austria). A reference vowel was recorded to allow audio signal calibration with a sound level meter. The NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada) was used to track the articulatory kinematics. During the study the participants wore an eyeglass frame with a reference sensor that served as the origin of the coordinate system, correcting for head movements. The articulators were tracked by five 3mm sensor coils glued at midline. PerAcryl 90 viscous glue (GluStitch, Delta, British Columbia, Canada) was used to attach the sensor coils to the articulators. The sensors were placed on the front of tongue (1cm back from tip- TF), mid tongue (halfway back from tip- TM), jaw (mandibular central incisors- J), upper lip (upper vermillion border- UL), and lower lip (lower vermillion border - LL). The positions of the articulators (x, y, and z) were reported in real time to a computer outside the sound booth through the Wavefront software (version 2.0, Northern Digital Instruments, 2016). A sampling rate of 22050 Hz was used to record the audio data and a rate of 400 Hz was used to collect the movement data.

Procedure

The sensors were glued on to the participants' tongue, lips, and jaw and then they were asked to speak for 20 minutes to adapt to the sensors. They were given several options to elicit 20 minutes of continuous speech, such as talking with the researchers, reading aloud a newspaper or magazine, and practicing sentences for a different adaptation study. Once the 20-minute adjustment period was over, the participants read six stimulus sentences that are listed in Table 1. The sentences included a variety of vowel and consonant sounds, requiring the articulators to perform some complex movements. *We do agree* was chosen because of the tongue and lip movements associated with the retracted and rounded vowels. Participants repeated each sentence four times in each of the following four conditions: normal voice (determined by the participant), soft voice (perceptually verified by the examiners), loud voice (perceptually verified by the examiners), and whispered. Each of the participants produced the speaking conditions in a randomized order.

Table 1

Sentences Read by Each Participant in the Four Different Speaking Conditions

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

Data Analysis

The experimenters segmented the fifth sentence (*We do agree the loud noise is annoying*) from the other utterances recorded by the participants using a custom Matlab application (version 2019b, The Mathworks, 2019). The words *we do* were segmented from the sentence using the microphone waveform to determine appropriate boundaries visually and then confirmed auditorily. Then the time-aligned kinematic record was used to determine the displacement and velocity of the lips when moving from the retracted to protruded (/i/ to /u/) position as seen in the lower panel in Figure 1, where a higher value represents greater lip protrusion. The differences in displacement and velocity of the articulatory movements were compared across the four speaking conditions.

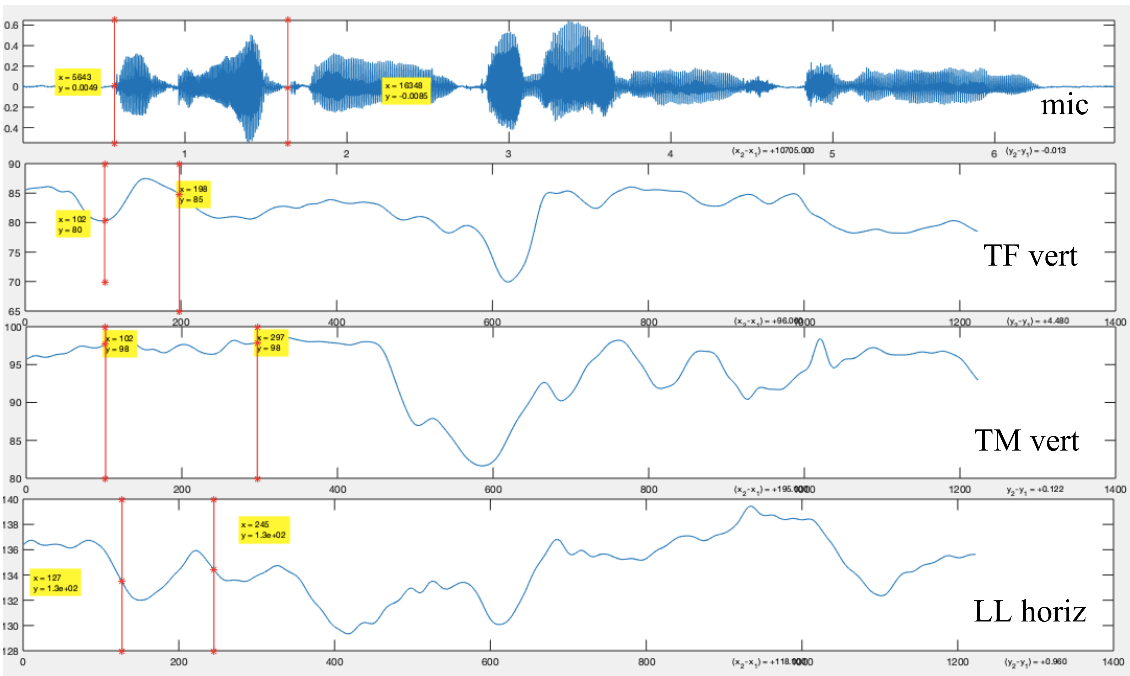

Figure 1. Sample sentence segmentation points. The segmentation points are shown by the red lines. The top panel shows the microphone waveform. The second panel shows the tongue front vertical movement. The third panel shows the tongue middle vertical movement. The bottom panel shows the lower lip horizontal movement.

Since the height of the tongue is influenced by jaw height, their movements were decoupled to estimate the relative contribution of the jaw to the net movement of the tongue at each sensor location. This was done by estimating the jaw's vertical movement for each sensor. The distance from the temporomandibular joint (TMJ) to each tongue sensor was divided by 110, which is an estimate of the average distance from the TMJ to the lower incisors in adults, based on previous research by Westbury, Lindstrom, and McClean (2002). The result was then used to scale the lower incisor's vertical movements and thus compute the contribution of the jaw to each tongue sensor's movement, both horizontally and vertically. Since the mandible is rigid, the sensor on the lower incisor directly measured the horizontal jaw movements (Richins, 2019).

Statistical Analysis

Measures from the first three error-free repetitions of the target sentence in each speaking condition were averaged prior to statistical analysis. A repeated measures ANOVA with concurrent contrasts was used to compare the kinematic differences in hull area, displacement and velocity of the articulators, as well as the jaw's contribution to the movements of the tongue front in the four speaking conditions. Speaker gender was included as a between-subjects factor. The comfortable condition was used as a baseline for contrast analyses with the loud, soft, and whispered conditions. Due to errors during data collection, all of the data from M3 and the data from the whispered condition of M1 were missing from the analysis.

Results

Significant changes in the dependent measures across the four speaking conditions are reported below.

Hull Area

Hull area refers to the kinematic articulatory working space or the area in mm^2 bounded by the movement of an articulator in the vertical and horizontal directions during an utterance. There was a significant main effect for all of the sensors. Hull area increased significantly (at $p < .05$) in the loud condition for the TM, TF, J and LL and in the whispered condition for the TM and TF. There was a significant decrease in the soft condition for the TF, J and LL. The descriptive statistics are found in Table 2 and the results of the repeated measures ANOVA in Table 3.

Table 2

Descriptive Statistics for Hull Area (mm²) Across the Experimental Conditions by Gender

		Hull Area							
		Comfortable		Loud		Soft		Whisper	
Sensor	Gender	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
TM	Female	17.43	8.94	29.41	15.51	13.07	7.11	23.83	13.44
	Male	29.97	13.73	50.69	27.12	30.52	17.11	38.72	20.53
TF	Female	32.79	18.80	48.60	26.03	27.11	13.73	45.43	22.89
	Male	45.33	13.06	68.98	36.31	42.56	14.57	53.10	24.61
J	Female	2.70	2.39	4.04	2.14	1.67	1.02	3.99	2.72
	Male	1.68	1.20	2.68	1.32	1.20	0.65	1.77	1.40
LL	Female	7.48	4.98	9.36	4.94	4.21	1.05	10.02	2.91
	Male	4.17	3.11	5.31	3.74	3.37	2.53	4.79	4.15

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

Table 3

Repeated Measures ANOVA and Concurrent Contrasts for Hull Area

	Hull Area															
	Main ANOVA				Loud Contrast				Soft Contrast				Whisper Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	2.66, 42.59	5.25	.001	.49	1, 16	21.72	<.001	.58	1, 16	2.44	.13	.13	1, 16	5.95	.027	.27
TF	2.34, 37.51	.90	.001	.41	1, 16	11.85	.003	.43	1, 16	5.37	.034	.25	1, 16	5.48	.033	.26
J	3, 48	.08	.001	.36	1, 16	10.16	.006	.39	1, 16	4.62	.047	.22	1, 16	3.57	.077	.18
LL	3, 48	.64	.001	.38	1, 16	4.60	.048	.22	1, 16	6.32	.023	.28	1, 16	3.35	.086	.17

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

Displacement

The repeated measures ANOVA revealed a significant main effect for displacement of all four sensors. There was a significant increase in the mean displacement for TM, TF and J in the loud condition and in the TM and J in the whispered condition. The TF, J and LL sensors showed a decrease in displacement in the soft condition. The differences for each of the conditions are depicted in Figure 2. The descriptive statistics are found in Table 4 and the results of the repeated measures ANOVA in Table 5.

Table 4

Descriptive Statistics for Displacement (mm) Across the Experimental Conditions by Gender

		Displacement (mm)							
		comfortable		loud		soft		whisper	
Sensor	Gender	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
TM	Female	5.46	2.00	6.88	2.60	4.74	1.69	6.70	2.10
	Male	6.15	0.99	7.49	1.86	5.75	1.61	7.56	2.31
TF	Female	9.17	1.93	10.91	1.66	8.81	2.33	10.67	3.10
	Male	9.51	3.90	10.67	5.09	8.41	3.47	10.28	3.40
J	Female	3.05	1.80	3.84	2.27	2.33	1.21	3.70	1.80
	Male	2.21	1.02	3.06	1.51	1.99	0.84	2.67	1.56
LL	Female	4.20	1.69	4.49	1.61	3.23	0.95	4.66	1.13
	Male	2.58	1.31	2.82	1.50	2.15	1.11	2.56	1.34

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

Table 5

Repeated Measures ANOVA and Concurrent Contrasts for Displacement

	Displacement															
	Main ANOVA				Loud Contrast				Soft Contrast				Whisper Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	3, 48	9.38	<.001	.37	1, 16	13.88	.002	.46	1, 16	2.97	.104	.16	1, 16	11.12	.004	.41
TF	2.06, 33.01	7.33	.002	.31	1, 16	9.75	.007	.38	1, 16	15.05	.001	.49	1, 16	4.41	.052	.22
J	3, 48	9.53	<.001	.37	1, 16	10.44	.005	.40	1, 16	5.22	.036	.25	1, 16	6.56	.021	.29
LL	3, 48	8.81	<.001	.36	1, 16	1.75	.204	.01	1, 16	13.10	.002	.45	1, 16	1.05	.322	.06

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

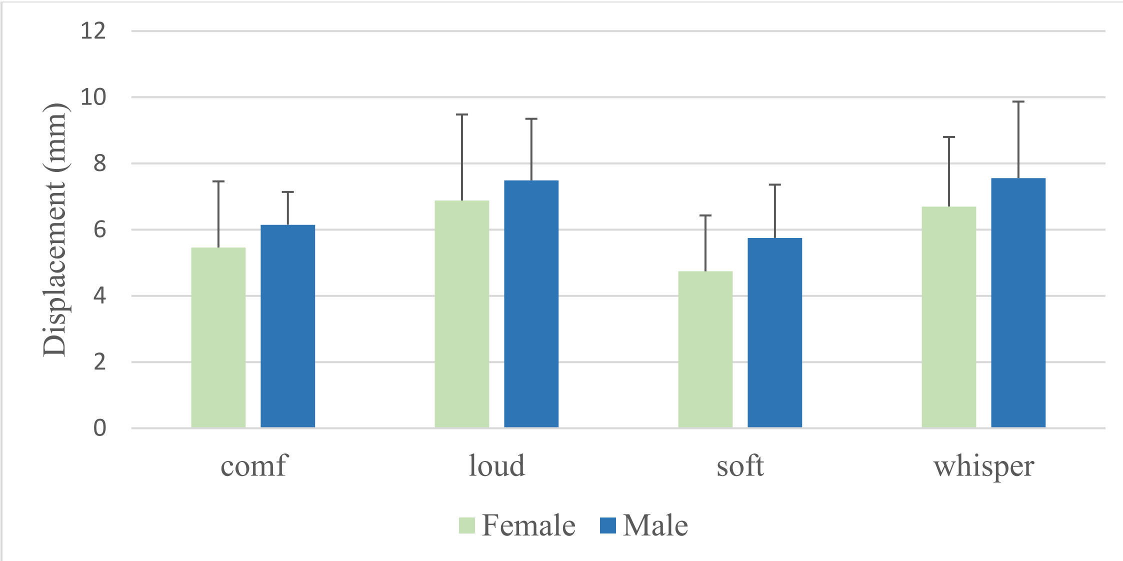

Figure 2. Mean displacement for middle of tongue.

Jaw contribution in millimeters. The results for jaw contribution in millimeters to the displacement of the tongue front followed a similar pattern as demonstrated by hull area and displacement with an increase in the loud and whispered conditions, as well as a decrease in the soft condition. The descriptive statistics for jaw contribution in millimeters are found in Table 6 and the results of the repeated measures ANOVA in Table 7.

Jaw contribution percentage. Similarly, for jaw contribution percentage there was an increase in the loud and whispered conditions but no significant change in the soft condition. The descriptive statistics for jaw contribution percentage are found in Table 8 and the results of the repeated measures ANOVA in Table 9.

Table 6

Descriptive Statistics for Jaw Contribution in Millimeters to Tongue Front Displacement Across the Experimental Conditions by Gender

		Jaw Contribution (mm)							
		comfortable		loud		soft		whisper	
Sensor	Gender	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
TF	Female	2.29	1.40	3.14	1.85	1.91	0.99	3.03	1.47
	Male	1.80	0.83	2.50	1.24	1.63	0.69	2.18	1.28

Note. TF = front of tongue

Table 7

Repeated Measures ANOVA and Concurrent Contrasts for the Contribution of the Jaw to Tongue Front Displacement

Main ANOVA				Loud Contrast				Soft Contrast				Whisper Contrast			
df	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
2.48, 39.66	11.02	<.001	.408	1,16	14.95	.001	.483	1,16	5.62	.031	.26	1,16	11.33	.004	.415

Table 8

Descriptive Statistics for Jaw Contribution Percentage Across the Experimental Conditions by Gender

		Jaw Contribution (%)							
		comfortable		loud		soft		whisper	
Sensor	Gender	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
TF	Female	24.88	11.38	29.06	15.85	21.88	7.16	30.10	14.62
	Male	21.60	13.04	28.05	16.65	22.32	9.22	26.04	20.65

Note. TF = front of tongue

Table 9

Repeated Measures ANOVA and Concurrent Contrasts for the Percentage Contribution of the Jaw to Tongue Front Movement

Main ANOVA				Loud Contrast				Soft Contrast				Whisper Contrast			
df	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
1.99, 31.98	3.77	.034	.191	1,16	13.02	.002	.449	1,16	.33	.573	.02	1,16	5.07	.039	.241

Velocity

A significant main effect was found for all of the sensors for velocity. The TM and J showed an increase in velocity in the loud condition. All the sensors showed a decrease in velocity in the soft condition. The descriptive statistics are found in Table 10 and the results of the repeated measures ANOVA in Table 11.

Table 10

Descriptive Statistics for Peak Velocity (mm/s) Across the Experimental Conditions by Gender

		Velocity (mm/s)							
		comfortable		loud		soft		whisper	
Sensor	Gender	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
TM	Female	84.07	30.29	98.32	33.48	70.73	26.35	84.68	30.31
	Male	98.70	22.50	119.81	33.00	91.83	16.42	117.63	32.67
TF	Female	115.64	27.83	115.94	25.42	108.41	28.24	114.21	40.17
	Male	123.21	61.68	129.53	62.50	111.02	53.48	131.29	51.14
J	Female	33.01	13.74	38.87	13.92	26.57	10.09	36.15	14.31
	Male	24.96	6.23	33.41	12.82	21.06	9.65	28.89	9.40
LL	Female	48.80	20.74	49.60	16.90	33.70	6.17	48.70	16.89
	Male	29.88	9.34	32.25	11.78	27.00	11.06	32.13	11.34

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

Table 11

Repeated Measures ANOVA and Concurrent Contrasts for Peak Velocity

	Velocity															
	Main ANOVA				Loud Contrast				Soft Contrast				Whisper Contrast			
Sensor	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES	*df*	*F*	*p*	ES
TM	3, 48	8.58	<.001	.35	1, 16	9.80	.01	.38	1, 16	7.96	.012	.33	1, 16	3.16	.094	.17
TF	3, 48	3.08	.036	.16	1, 16	.61	.444	.04	1, 16	11.74	.003	.43	1, 16	.39	.540	.02
J	2.11, 33.68	11.46	<.001	.42	1, 16	13.47	.002	.46	1, 16	15.51	.001	.49	1, 16	2.34	.146	.13
LL	3, 48	8.48	<.001	.35	1, 16	.61	.448	.04	1, 16	9.43	.007	.37	1, 16	.31	.587	.02

Note. TM = middle of tongue, TF = front of tongue, J = jaw, LL = lower lip

Discussion

The present study examined the relationship between the larynx and the vocal tract, or how vocal fold activity affects articulatory movements. The results support the original hypothesis that the articulatory kinematics would vary for each speaking condition compared to the comfortable loudness condition. The soft condition generally had smaller and slower articulatory movements than the comfortable condition, whereas the whispered condition showed an increase in size and the loud condition showed the greatest increase in both size and speed compared to the comfortable condition. This trend is represented in Figure 2, which demonstrates the differences in displacement of the middle tongue for each of the conditions.

Loud

When compared to the comfortable speaking condition, the articulatory movements increased in size and speed in the loud condition. The hull area of the TM, TF, J and LL was significantly larger for loud speech compared to comfortable speech. The displacement increased for the TM, TF and J and the velocity increased for the TM and J in the loud condition. The jaw contributed more (in millimeters and as a percentage) to tongue height for loud speech.

The data suggest that loud speech involves a scaling up of the characteristics of normal speech. In order to increase vocal intensity, more subglottal pressure is generated which also increases supraglottal pressure. With greater pressure in the pharynx and oral cavity, the articulators must exert more effort to contain this pressure and produce intelligible speech sounds. The articulatory movements are larger and faster to better constrict the vocal tract to prevent turbulent airflow that would distort speech. The increased movements also widen the vocal tract to project more acoustic energy in loud speech (Schulman, 1989). The widening of the vocal tract is evidenced in the positioning of the articulators, particularly the jaw and lower lip as found in this study and several others (Dromey & Ramig, 1998; Geumann, 2001; Huber & Chandrasekaran, 2006; Schulman, 1989;). An increase in vocal tract movement in loud speech was also found in a study by Dromey et al. (1995) as evidenced by changes in the second formant transition duration, extent, and rate. These findings suggest that "loud speech might be viewed as a naturally occurring scaling transformation, which modifies the activity of all muscles in the articulatory linkage" (Dromey et al., 1995, p. 761)

Soft

The soft condition reduced the size and speed of the articulatory movements. In the soft condition the TF, J and LL showed a smaller hull area as well as smaller displacement values than the comfortable condition. All of the sensors (TM, TF, J and LL) decreased in velocity in the soft condition. There was also less jaw contribution in millimeters for soft speech but no significant difference in the jaw contribution percentage.

These results suggest that there is a correlation between vocal intensity and the size of the articulatory movements; they increase from soft to comfortable to loud (Dromey et al., 1995; Whitfield, Dromey, & Palmer, 2018). If loud speech is an amplification of normal speech, then soft speech is characterized by a reduction in movement amplitudes. The smaller movements are associated with a narrower vocal tract, with a weaker projection of acoustic energy.

Whispered

When producing whispered speech, the vocal folds do not vibrate as turbulent airflow is exhaled. In the current study the articulatory movements were larger than comfortable speech, but smaller than loud speech. Compared to the comfortable speaking condition, the whispered condition showed an increase in hull area for TM and TF, displacement for TM and J, and jaw contribution in millimeters and percentage, which equates to larger movements of the tongue and jaw. Since whispering is primarily used in quiet environments or to prevent other parties from hearing, it is not the typical mode of communication and is less familiar than modal phonation. More articulatory effort is exerted to speak in a whisper because it is less familiar to speakers (Jovičić & Šarić, 2008). Without phonation, speech produces less sound energy that can be used for auditory feedback; therefore, articulation may rely more on tactile feedback in whispered speech. It could be speculated that the increase in movement size is related to the diminished auditory feedback and the unfamiliarity of whispered speech. In contrast to the present results, Barber (2015) found a decrease in hull area for TM and TF in the whispered condition when analyzing the hull area for a whole sentence. The difference in phonetic context, a whole sentence versus a single syllable, may account for the differing results. Although the articulators produced larger movements in whispered speech, there was no significant effect on velocity. Barber also found that velocity remained fairly similar in the whispered condition.

Limitations and Directions for Future Research

The current study provides insight into the connection between phonation and articulation under four speaking conditions. The inferences we can draw are nonetheless subject to certain limitations. The participants repeated the target sentences multiple times in each of the speaking conditions with 3mm sensor coils glued to their articulators. This study examined the articulatory kinematics of one of the sentences produced multiple times. While this method was necessary to collect data using the electromagnetic articulography and directly compare these data between and across participants, it is not fully generalizable to typical speaking patterns. When the sensors were attached, the participants spoke continuously for 20 minutes to provide time for adaptation before these data were collected; however, some participants might have needed more than 20 minutes to fully adapt to the sensors. The sensors may reduce the tactile feedback used in speaking and the lack of adaptation may cause acoustic and perceptual changes compared to typical speech. Despite these limitations, the findings provide insight into the speech mechanism and are a basis for future studies that may include a longer adaptation period or different sensor placement as well as longer or more natural speech stimuli.

Implications for Practitioners

Based on these results as well as previous research, soft speech produces smaller and slower articulatory movements than a comfortable speaking voice, whispered speech produces larger articulatory movements, and loud speech produces the largest and fastest articulatory movements. These findings are valuable to clinicians who are working to improve the intelligibility of their clients with articulation and/or voice disorders. If the problem is reduced movement, as in hypokinetic dysarthria, clients would benefit from using a louder speaking voice, since it increases articulatory excursions and therefore also increases the likelihood of reaching articulatory targets which will consequently improve intelligibility. When an individual speaks loudly, the vocal folds adjust their tension and closure to achieve the target volume (Behrman, 2013). Since the speech subsystems are closely connected, the respiratory system and vocal tract naturally modify their movements in response to the changes in the vocal system. By simply focusing on loud speech, phonation, articulation and respiration can all improve which produces clearer, more intelligible speech. Voice therapy that targets increased loudness, such as LSVT Loud (Dromey et al.,1995) and PhoRTE (Ziegler, Verdolini Abbott, Johns, Klein, & Hapner, 2014), reaps the benefits of the interconnected speech system with improvements to articulation and respiration as well.

Conclusion

The present study investigated the influence of laryngeal activity on articulation by comparing the articulatory kinematics of soft, loud and whispered speech to the comfortable speaking voice. The findings revealed significant differences between the conditions, indicating that phonation does influence articulation. In loud speech, the articulators moved farther and faster. Most of the movement measures also increased in the whispered condition, although not as much as in loud speech, and the velocity remained fairly constant. For soft speech the movement size and speed decreased compared to the comfortable speaking condition. These results support previous findings that the articulatory movements increase with loudness (Dromey et al., 1995; Whitfield et al., 2018). This interaction is useful in understanding the speech mechanism and using it to our advantage to improve speech intelligibility.

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APPENDIX A

Annotated Bibliography

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

Objective: Examine the effects of speaking rate on the velocity of lower lip and tongue movements. *Method:* 5 participants produced a phrase 10 different times at 5 speaking rates. They were told that their normal speaking rate was a 10 and then asked to adjust their rate based according to a number (i.e. 20 to double their speaking rate). Their production was recorded by radiodense markers placed on the articulators that were tracked using an x-ray microbeam system. *Results:* The data showed an increase in movement duration as speaking rate decreased. Faster speaking rates had symmetrical velocity profiles with one relatively large velocity peak, unlike the asymmetrical velocity profiles and multiple peaks at slower rates. *Conclusions:* The variability in velocity profile shape suggests that at slower speaking rates, speakers receive more feedback and that the movement gestures consist of several sub-movements. *Relevance to current work:* This article revealed the association between speaking rate, movement duration and velocity profile shape. Since the current study will also analyze articulatory kinematics it will be important to consider speaking rate as a possible contributing factor to the results. Individual speakers may have different natural speaking rates, which may be adjusted with the various speaking conditions and therefore contribute to the results.

Barber, K. M. (2015). *The effects of laryngeal activity on articulatory kinematics* (Unpublished master's thesis). Brigham Young University.

Objective: Examine the interaction of the voice source and vocal tract, by comparing three speech conditions (voiced, whispered and mouthed) and their effects on the kinematics of articulation. *Method:* Twenty participants read six stimulus sentences in each of the speech condition into a microphone. NDI Wave electromagnetic articulography was used to record the articulatory movements from 5 sensors glued on the articulators and a reference sensor on eyeglasses. The study analyzed sentence duration, articulatory stroke count, stroke distance, peak speed, and hull volume. *Results:* The results revealed the most changes in articulation between the voiced and mouthed conditions. The mouthed condition showed an increase in sentence duration and articulatory stroke count, and a decline in stroke distance but no change in stroke duration. There was an increase in the number of articulatory strokes and a slight decline in peak speed during the whispered condition. There was no change in peak speed of the lips or stroke duration in the whispered condition compared to the voiced condition. There was a significant increase in hull volume (articulatory working space) for UL but a decrease for TM and TF in whispered and mouthed conditions compared to voiced. The peak speed was found to be greater for females than males in all speaking conditions. Males showed more variation than females in peak speed. Females showed greater stroke distance than male participants throughout the study. *Conclusion:* The voiced and mouthed conditions revealed more articulatory differences between them at the sentence level. The mouthed condition showed significant changes in stroke count, peak speed and stroke distance compared to the voiced condition. This is attributed to the lack of auditory and laryngeal feedback compared to normal speech, which likely encouraged more conscious awareness of the articulators and exaggerated movements to help with lip reading. These findings suggest that laryngeal activity influences articulation. *Relevance to current work:* The research question and methods used in this study are very similar to the current study, in that they both use NDI Wave electromagnetic articulography to analyze articulatory kinematics during contrasting speech conditions. The findings of this study support the hypothesis that there will be articulatory differences between the various speech conditions.

Behrman, A. (2013). *Speech and voice science.* San Diego, CA: Plural Publishing.

Relevance to current work: This chapter discusses the acoustic theory of speech production, also known as the source filter theory, which is foundational to understanding the interaction of the larynx and the articulators. The phonating vocal folds are the speech sound source in voiced sounds. The sound source creates harmonics. The sound is then resonated in the vocal tract, amplifying certain frequencies called formants which distinguish individual speech sounds. The acoustics produced reveal aspects of laryngeal or articulatory activity. This interaction will be further explored in the current work by analyzing the difference in articulatory movements for voiced, whispered, soft and loud speech.

Brunner, J. & Hoole, P. (2012). Motor equivalent strategies in the production of German / ʃ / under perturbation. *Language and Speech, 55*, 457-476. doi.org/10.1177/0023830911434098

Objective: Investigate motor equivalence by perturbing speech production and analyzing the effects in adaptation. *Method:* Six participants received a palatal prosthesis to perturb speech production. Three received an alveolar palate where the alveolar ridge was moved posteriorly and three received a central palate where the alveolar arch was lowered and flattened. They were asked to wear the prosthesis every day for two weeks. They were recorded while producing the target sound / ʃ / in a nonsense word using electromagnetic articulography. During the first session, they were presented with white noise over headphones to mask auditory feedback. The acoustics were analyzed by segmenting the target sound in PRAAT, applying a band-pass filter and calculating the spectral parameters. The position of the lip and tongue tip were estimated from the position of the corresponding sensor. *Results:* Only one speaker demonstrated perfect motor equivalence as demonstrated by a positive correlation between the tongue and lip but without correlation of the articulatory and acoustic parameters. 3 speakers demonstrated partial motor equivalence and 2 speakers showed no motor equivalence. The results were mixed between participants with both types of palates, so the presence or absence of an articulatory landmark is not a causal factor in motor equivalence. The participants were able to adapt their articulatory movements without auditory feedback which invalidates the auditory feedback hypothesis. *Conclusion:* The speaker's adaptation of the target phoneme / ʃ / depended more on tongue position, rather than the correlation of lip and tongue positions. Speakers adapt the position of their articulators to reduce acoustic output variability. Motor equivalence is not dependent on tactile or auditory feedback. *Relevance to current work:* This study demonstrates that electromagnetic articulography is an effective way to record articulatory movements and analyze motor equivalence.

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

Objective: Understand the effects of botulinum toxin type A on fluency and vocal function when treating adductor spasmodic dysphonia (ADSD) across various severity levels. The study also sought to evaluate the expert's perception of fluency and voice quality. *Method:* The participants included 42 English-speaking adults with ADSD and age-matched controls. They were recorded within 2 weeks before their first botulinum toxin type A injection and 2-6 weeks after the injection. 12 certified speech-language pathologists were chosen as listeners in 2 expert panels. They listened to the speech samples and rated them using a custom visual analog scale (VAS) software application. *Results:* The individuals with moderate ADSD showed significant improvement in roughness and brokenness. Those with severe and profound ADSD showed significant improvements on overall voice quality, roughness and brokenness, but not on breathiness. Those with mild ADSD became breathier and did not improve significantly on any voice attribute. All the individuals with ADSD, except the group with mild ADSD, significantly improved in overall fluency, spasms and tension; however, they were still rated as significantly less fluent than the controls. Older participants with ADSD also showed less improvement than younger participants. *Conclusion:* The results indicate that botulinum toxin type A is effective in improving fluency and voice quality in more severe cases of ADSD, but not in mild ADSD. Younger individuals respond better to botulinum toxin type A injections than older individuals. Using a computerized VAS method such as the one in this study is shown to be a reliable and sensitive way for experts to rate voice quality and fluency. *Relevance to current work:* This article examines effects of a change in the laryngeal activity (after injecting botulinum toxin type a) on fluency and voice quality. The current study will examine effects of changes in laryngeal activity on articulation. It would be interesting to see how botulinum toxin type A treatment for ADSD affects articulation.

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.org/10.1093/brain/111.2.439

Objective: Evaluate the coordination of speech movements in individuals who stutter. *Method:* 6 males who stutter and 5 typical males participated in the study. They repeated the utterance "sapapple" over 140+ times and their speech movements were tracked using cantilever beams with strain gauges on a head mount. *Results:* There were no significant differences in range of movement or velocity of the articulators between the group of stutterers compared to the control group. These data suggest that individuals who stutter are able to produce smooth single-peaked velocity profiles similar to typical speakers. There were differences in multimovement coordination between groups as evidenced by aberrant sequencing of movement onsets and peak velocities in those who stutter. Typical speakers were consistent in their movements when producing the utterance. The data did not show the same consistency in the participants who stuttered. *Conclusions:* Individuals who stutter presented with differences in sequencing the articulatory movements, even when speaking fluently. These results indicate that the impairment in speech production likely occurs at a neurological level. *Relevance to current work:* This article discusses the ability to track articulatory movements in order to understand the coordination, sequencing, range and speed of the various articulators. The current work will also analyze these concepts of speech kinematics.

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, UK: Oxford University Press. doi.org/10.1093/acprof:oso/9780199235797.001.0001

Relevance to current work: This chapter aimed to describe the articulatory changes that arise as a result of targeting the larynx in treatment by using the data from three speech disorders. If focusing on one component, such as loudness, also influences respiration, phonation and articulation, it would be important to know about it, in order to make treatment more effective. Typically, disorders are viewed as one isolated problem, either of vocal activity or speech production, but the results from the three disorders discussed indicate that the source and filter have a stronger connection than previously theorized and that focusing treatment on one aspect will likely influence the other. Research has shown that the increased speech effort in LSVT leads to changes in the articulatory movements as evidenced by the acoustical differences and larger lip movements in individuals with Parkinson's disease. By simply attempting to speak louder, an individual's respiratory system, vocal folds and vocal tract make the appropriate adjustments to allow for more intelligible speech, which simplifies therapy and provides faster, more efficient results. Although laryngeal spasms are the primary characteristic of adductor spasmodic dysphonia, there is some evidence that suggests it is more than a pure voice disorder. These spasms disrupt the rate and fluency of articulation and are associated with significant unsteadiness in the lips and second formant. After treatment (botulinim toxin injections) speakers with SD showed improvements in voice quality, fluency and lip movements. There are several possible explanations for the kinematic differences including a secondary disorder of the vocal tract, a natural connection in the coordination of the larynx and vocal tract, or the development of compensatory strategies. Muscle tension dysphonia is commonly associated with tension in the muscles of the larynx which leads to a strained, breathy voice quality. The laryngeal muscles attach to the hyoid bone, and so do muscles of the tongue and jaw, which suggests that the muscle tension could also affect articulation, although the effects appear to be subtle perceptibly. Treatment for MTD often consists of circumlaryngeal massage, and posttreatment data show increase movements of the articulators as evidenced by diphthong formant transitions. The exact cause of the changes to articulation remain unclear, but the findings included in this review of these three voice disorders suggest that treatment targeting the larynx will have carryover effects into supraglottal articulation.

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.org/10.1044/1092-4388(2008/015)

Objective: Determine the effects of successful voice treatment for muscle tension dysphonia (MTD) on supraglottal articulation. *Method:* 111 women with MTD and were recorded pre and post-treatment while reading the *Rainbow Passage*. Treatment consisted of manual circumlaryngeal techniques. Their productions were compared to a control group of 20 women. The acoustics were analyzed based on the transition extent, duration and slope for F1 and F2 in the diphthongs /eI/ and / ɑI/. Each recording was also analyzed for passage timing measures using a custom MATLAB application and perceptual ratings. *Results:* The data showed significant differences in /ɑI/ F1 slope and transition extent, /eI/ transition duration, F2 slope and F2 extent as well as sample duration, speaking time ratio and perceptual severity between the 2 groups of participants. The group of speakers with MTD demonstrated significant changes in the formant slopes and transition extents for both diphthongs, sample duration, speaking time ratio and perceptual severity, whereas the control group did not show significant changes in any of the variables. Higher severity ratings of MTD correlated with shallower formant transition slopes, longer overall sample duration and lower speaking time ratio. Individuals who had the most improvements in voice quality after treatment tended to have a greater increase in /ɑI/ F2 slopes and transition extents, decreased sample duration and increased speaking time ratio. *Conclusions:* The acoustic differences pre and post-treatment suggest that improving laryngeal function through voice treatment also affects vocal tract movement. These findings indicate that MTD may be more than a disorder of the vocal folds since it has effects on speech production as well. *Relevance to current work:* The findings of this article suggest that changes to laryngeal activity affect movement of the vocal tract, which supports the hypothesis for the current study.

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.org/10.1044/jshr.3804.751

Objective: Understand the effects of increasing vocal intensity on phonation and articulation in individuals with Parkinson's disease. *Method:* A 49-year-old man with Parkinson's disease participated in this case study. He received 16 sessions of the Lee Silverman Voice Treatment over 4-weeks. His performance was tracked pre and post-treatment using tidal volume, forced vital capacity, maximum phonation time, maximum fundamental frequency range while producing a syllable series and reading the "Rainbow Passage". Vocal fold adduction was assessed pre and post-treatment with videostroboscopy. Articulation was also assessed using frication duration, rise time and a ratio of the vowel to whole-word duration. *Results:* Following treatment, the participant was able to increase and maintain his vocal intensity voluntarily. The data showed an improvement in phonatory stability, fundamental frequency variability, transition extent in the second formant, vocal fold adduction and subglottal air pressure. *Conclusion:* Increasing vocal intensity in patients with Parkinson's disease through intensive treatment, such as LSVT, improves phonation and articulation. *Relevance to current work:* This study supports the theoretical basis for the current work that changes in laryngeal activity have concomitant effects on articulation.

Huber, J. E. & Chandrasekaran, B. (2006). Effects of increasing sound pressure level on lip and jaw movement parameters and consistency in young adults. *Journal of Speech Language Hearing Research, 49,* 1368–1379. doi.org/10.1044/1092-4388(2006/098)

Objective: Examine how task demands to increase sound pressure level affect speech kinematics. *Method:* 30 normal young adults, 15 men and 15 women, read two short sentences 15 times in each of the four conditions. The four conditions consisted of comfortable loudness, twice their comfortable loudness, between a target SPL range (as shown on an SPL meter) and with background noise. Markers were attached to the participant's skin which tracked the kinematics of their lips and jaw using infrared light emitting diodes and a camera system. The articulatory kinematic measurements were made with MATLAB algorithms. *Results:* Each of the cues to adjust loudness resulted in a similar SPL increase (about 10dB). Speakers tended to slow their speech rate in the background noise condition. There were changes in the articulatory kinematics when speaking at higher loudness levels; however, the differences were not dependent on the type of cue. The different articulators responded differently when increasing vocal intensity. The upper lip was the most variable, lower lip and jaw were responsible for opening the mouth with increased loudness and F1. Once they were able to maintain the SPL level, their production consisted of the same exact movements repeated for each consecutive attempt. *Conclusion:* Movement patterns are not dependent on the type of cue given to elicit an increase in SPL. Increasing vocal loudness does affect the movement patterns of the articulators. *Relevance to current work:* This article suggests that increasing vocal loudness alters articulatory kinematics, which suggests that the current work will have similar results.

Jovičić, S. T. & Šarić, Z. (2008). Acoustic analysis of consonants in whispered speech. *Journal of Voice, 22,* 263-274. http://doi.org/10.1016/j.jvoice.2006.08.012

Objective: Discover the difference in consonant production when whispered compared to voiced. *Method:* Six speakers produced all 25 of the Serbian consonants in carrier sentences that placed the consonants between in the initial, medial and final position of the sentences in normal voiced and whispered conditions. The productions were recorded, manually segmented and analyzed for VOT, pauses, frication, formant trajectories, RMS intensity temporal trajectory and perceptual impression. *Results:* Segmenting the whispered sentences proved to be much more difficult than segmenting the voiced sentences because of the missing features on the waveform due to lack of voicing and low intensity and special criteria had to be developed. Individual consonants and whole sentences had longer durations in the whispered condition than voiced condition. It is theorized that the increase in duration may be due to increased awareness and more control required to articulate intelligible speech when whispered. As expected, there was a significant decrease in intensity in whispered speech. They found differences in intensity based on the place and manner of the consonant being produced and that the intensity of unvoiced consonants remained fairly constant in the both voiced and whispered conditions. *Conclusions:* Whispered speech results in longer consonant durations and lower intensity than normally phonated speech. Whispered speech takes longer because of the increased effort required for articulation. *Relevance to current work:* The results of this article suggest that whispered speech affects articulation as evidence by longer consonant durations, which supports the hypothesis that there will be differences in the articulatory kinematics for the different speaking conditions.

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

Objective: Investigate the coordination of the larynx with the lips and jaw in the production of voiceless consonants when perturbing an articulator mechanically. *Method:* Three healthy subjects produced a nonsense phrase 400 times while receiving perturbations from a paddle on the lower lip. Their lip and jaw movements were recorded with a modified Selspot system and their laryngeal movements were recorded with transillumination through a nasal endoscope. The lower lip was perturbed three times, just before the vowel offset, early during oral closure and late during oral closure. *Results:* When the lip was perturbed, it delayed and lengthened the duration of laryngeal abduction. The perturbed condition also modified the movements for oral release, including movement velocity and displacement of the articulators. *Conclusions:* Lip perturbation during the production of voiceless stops alters laryngeal activity. This indicates a strong connection between the movements of the larynx, lips and jaw. *Relevance to current study:* The results indicate that a change in any of the articulators will affect the movements of the other articulators. While this article examined the effects of lip and jaw perturbation on the larynx, the current study will investigate the influence of laryngeal activity on the supraglottal articulators, which is a more natural phenomenon in speech production. If the articulators are as tightly coupled as this study suggests, there will be a strong correlation in the present study as well.

Perkell, J. S., Matthies, M. L., Svirsky, M. A., & Jordan, M. I. (1993). Trading relations between tongue-body raising and lip rounding in production of the vowel /u/: A pilot "motor equivalence" study. *Journal of the Acoustic Society of America, 95*, 2948-2961. doi.org/10.1121/1.405814

Objective: Investigate motor equivalence in speech production as a result of reciprocal adjustments to articulatory movements. *Method:* Four participants selected to participate in the study based on their strong lip protrusion during production of the phoneme /u/. Data were collected using an electromagnetic midsagittal articulometer (EMMA) to track and record movement of the articulators. The participants read several phrases which included the target sound /u/. In order to compare the area function in the velopalatal and lip regions with the articulatory data, dental casts were made of the participants' hard palates and video recordings of their lips. The dental casts were traced and scanned into a computer to calculate the cross-sectional area. The participants produced multiple repetitions of /u/ to compare the differences in articulatory movements as well as acoustics. *Results:* The data showed a correlation between tongue height and lip rounding. *Conclusion:* These findings support the motor equivalence theory. *Relevance to current work:* This study indicates that the phoneme /u/ can be produced in various ways and still be accepted in American English, which is critical in analyzing the articulatory movements of the /u/ phoneme in the current study.

Schulman, R. (1989). Articulatory dynamics of loud and normal speech. *Journal of the Acoustical Society of America, 85*, 295–312. doi.org/10.1121/1.397737

Objective: Compare normal and loud speech production in terms movement and timing of the lips and jaw in bilabial stops and stressed vowels. *Method*: Four Swedish speakers participated in the study. Magnetic coils were placed on the lips and teeth to record the articulatory movements using a magnetometer system. Adduction and abduction of the vocal folds were recorded with electroglottography. The participants read six lists of words with the phoneme /b/ and each of the 12 Swedish vowels in the normal voice and then shouted condition. The recordings were analyzed to examine displacement, velocity, timing, coarticulatory interactions and acoustic segmental duration. *Results:* The data showed similar jaw position in both conditions during vowel production. The influence of coarticulation was less clear in the loud condition compared to the normal condition. In loud speech, the upper lip compensates for the lowered jaw, demonstrating the principle of motor equivalence. There is not a simple linear amplification of articulatory movement from normal to loud speech; it is a much more complex interaction. As displacement increases so does velocity, which results in shorter durations of bilabial stops but longer durations for vowels in the loud condition. *Conclusions:* Loudness is associated with larger displacement and higher velocities of the articulators. It is theorized that this is either in response to production demands or perceptual constraints. *Relevance to current work:* Both studies compare loud speech to normal speech. It is likely that the current study will provide similar results including an increase in displacement and velocity in the loud condition.

Sharifzadeh, H. R., McLoughlin, I. V., & Russell, M. J. (2012). A comprehensive vowel space for whispered speech. *Journal of Voice, 26*, E49–E56. doi.org/10.1016/j.jvoice.2010.12.002

Objective: Present a comprehensive vowel formant space for whispered speech compared to normally phonated speech. *Method:* 10 middle-aged (five men and five women) volunteers from Birmingham, England participated in the study. The subjects read lists of words with the 11 vowels 10 times (five times in a normal speaking voice, five times whispered) while being recorded in a sound booth. The recordings were segmented, and the formants were analyzed using an automatic approach. The results were compared and reported separately for men and women. *Results:* Whispered vowels converge with adjacent vowels compared to normally phonated vowels for both men and women, especially for central mid vowels, compared the extreme front and back vowels. Both the first and second formants are raised in the whispered condition; however, the first formant shows a more significant difference. The third formant remains fairly stable in both conditions. Women tend to lower their tongue position in the whispered condition. The vowel quadrilateral changed by 9% in both height and width for men and had a 6% decrease in width and 21% increase in height for women. *Conclusions:* The formants and vowel space are different for voiced and whispered speaking modes. The extent of the change depends on the place of articulation, with central vowels experiencing more of a change. These results are based on the British West Midlands accent and may be different for other dialects. *Relevance to current work:* This article examines vowel space for whispered speech. The current study will analyze the articulatory changes of the vowel /u/ for normal, whispered and loud speech. Based on this article, the first and second formants will likely be raised in the whispered condition, which indicates that there is a change in the vocal tract configuration and supports the hypothesis for the current work.

Simmons, K. L. (2016). *Bidirectional interference between simulated driving and speaking* (Unpublished master's thesis). Brigham Young University.

Objective: Examine the effects of dual-task interference on performance while speaking and driving simultaneously. *Method:* 60 adults participated in the study (30 male, 30 female). The participants performed the driving and speaking tasks separately at first and then concurrently. They had previously selected eight interesting conversational topics which they were presented with one at a time during the experiment and asked to talk about it in a monologue. Their speech samples were analyzed using Praat to compute the mean and standard deviation of F_0 and intensity. The proportional time spent speaking versus talking was measured with a custom Matlab application. Their driving abilities were recorded and analyzed using the OpenDS software and a specific driving course. Their performance on the driving task alone versus the simultaneous driving and speaking tasks was compared using the mean and standard deviation of speed, lane position variation, steering wheel position variation and number of steering wheel turns. These data were saved and imported into a custom Matlab application. *Results:* During the divided attention task, the participants' speaking time ratio decreased, mean intensity increased, average speed slightly increased, steering wheel position variation increased and number of adjustments to the steering wheel increased. The findings were tested for age and gender effects. The result showed that compared to the other age groups, the participants in their 20's had less intensity and F_0 variation, less deviation from the center lane and less variation in steering wheel position. The 60's group had more speed variation. As for gender, males had more variation in their intensity level and females in the 40s group deviated further from the center of the lane. *Conclusions:* The results support the hypothesis that when performed concurrently, both speaking and driving performance would decrease. This is evidence of the negative effects of multi-tasking. *Relevance to current work:* This article shows the effects of multi-tasking on laryngeal activity (variation in F_0 and intensity). The current study will analyze the effects of changes in laryngeal activity (increased intensity) on articulation, which could also be affected during multi-tasking and further decrease speech performance.

Tasko, S. M. & Westbury, J.R. (2002). Defining and measuring speech movement events. *Journal of Speech, Language, and Hearing Research, 45,* 127–142, doi.org/10.1044/1092-4388(2002/010)

Objective: Provide a detailed description of how to identify movement units based on pellet speed. Use and apply the results to streams of orofacial movements. *Method:* 18 speakers' recordings were selected from the University of Wisconsin Microbeam Speech Production Database (XRMB-SPD). The speakers read an expanded version of the Hunter script. Their articulatory movements were recorded and tracked using five gold pellets glued on the tongue, between the mandibular incisors, and on the lower lip. In order to segment and quantify the kinematic data they used speed history to find boundaries where the velocity slowed down, assuming that is an indication of the preparatory phase to change directions or movements. Then segments were used to calculate the stroke distance, stroke duration, peak stroke speed and boundary speed. *Results:* It is difficult to match the kinematic data with specific sounds, syllables or words. There are usually fewer strokes than sound pairs, but more than syllables or words and the number of strokes is not consistent between articulators. The timing of strokes for the different articulators is not clearly synchronized, each one beginning and ending at slightly different points in time. The strokes do not directly correlate with acoustical durations. Due to these difficulties, a procedure is needed in order to divide kinematic waveform strokes. The method of using speed history appears to be effective in automated stroke identification without reference to external bodily movements. It can likely be applied to all types of motor tasks. However, it is improbable to assume that the strokes can be directly connected with speech targets. As currently used, it is only appropriate for movement within planes or in three-dimensional spaces but not for more complicated movements that involve translating and rotating. There may also be errors in detecting the stroke boundaries due to poor signal-to-noise ratio. *Conclusions:* Using speed history to parse stroke boundaries appears to be an effective method for segmenting kinematic data. *Relevance to current work:* The current study will analyze kinematic data and the method described in this article will likely be helpful.

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. Retrieved from https://www.researchgate.net/publication/290609300_Phonatory-articulatory_relationships_Do_speakers_with_spasmodic_dysphonia_show_aberrant_lip_kinematic_profiles

Objective: Investigate the relationship between the larynx and articulators in spasmodic dysphonia. *Method:* There were four participants in the study (two men and two women). One of the men had severe adductor spasmodic dysphonia (ADSD), one of the women had mild ADSD and the other woman had abductor spasmodic dysphonia (ABSD). Their results were compared with a male control. Their articulatory movements were tracked with a strain gauge transducer system on the upper and lower lips while they repeated the phrase *buy Bobby a puppy*. They repeated the phrase twenty times in voiced and whispered conditions. The kinematic data were analyzed both quantitatively and qualitatively. The analysis included describing the smoothness of the lower lip velocity profile shape, the average of the velocity peaks for the first lower lip cycle, the spatiotemporal index (STI) and continuous correlation function (CCF). *Results:* In the first lower lip cycle, the typical speaker and the speaker with mild ADSD had velocity profiles with one or two peaks, whereas, the speaker with severe ADSD and the speaker with ABSD had multiple velocity peaks. The number of velocity peaks was reduced in the whispered condition for the speaker with severe ADSD. The STI values for all the participants were similar, which indicates that the number of laryngeal spasms was consistent across repetitions. The STI values decreased for all speakers with SD in the whispered condition. As hypothesized, the speaker with severe ADSD and the speaker with ABSD showed greater fluctuations in the CCF during the voiced conditions; however, it remained close to -0.9 for the typical speaker and the speaker with mild ADSD. *Conclusions:* The individuals with more severe cases of SD showed differences on the articulatory kinematic measures, which indicates that the severity of vocal spasms influences the impact they have on articulation in individuals with spasmodic dysphonia. The speaker with severe ADSD presented with values close to the control speaker's values in the whispered condition, which suggests that laryngeal spasms may cause disturbances in the supralaryngeal movements. However, there are other factors to consider since there were still some supralaryngeal disturbances in the whispered condition. *Relevance to current work*: This article examined the articulatory kinematics in individuals with spasmodic dysphonia in voiced and whispered conditions. The current work will examine the articulatory kinematics of typical speakers in voiced, soft, loud and whispered condition.

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.

Compensation

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

Participation

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.

Questions about the Research

If you have questions regarding this study, you may contact Christopher Dromey at (801) 422-6461 or dromey@byu.edu for further information.

Questions about Your Rights as Research Participants

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: _____________