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Articulatory Kinematic Compensation for a Bite Block During Diphthong Production

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Master of Science

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ABSTRACT

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The current study examined the effects of bite blocks on articulatory kinematics when producing diphthongs /ɑɪ/ and /ɑʊ/ within a phrase. Participants consisted of 20 young adults (10 males, 10 females) with no speech, language or hearing disorders. Participants produced the diphthongs in the carrier phrase *I'm an owl that hoots.* A Northern Digital Instruments Wave electromagnetic articulograph measured the articulatory movements while the speaker produced the stimuli in two conditions (pre bite block insertion and post bite block insertion). Bilateral bite blocks were made using Express dental putty, which is a silicone impression material, in order to create a 10 mm inter-incisal gap. Marker distance, maximum speed, and jaw contribution to tongue movement for three sensors (tongue back, tongue mid, tongue front) were calculated for the diphthongs segmented from the carrier phrase. F1 and F2 transitions and rate were also calculated for each diphthong. Results revealed kinematic differences during diphthong production after the bite block was inserted. Tongue movements independent from the jaw increased after the bite block was inserted, especially during production of the diphthong /ɑʊ/. Bite block by gender interactions during production of the diphthong /ɑɪ/ revealed larger and faster initial movements for males. The results did not reveal any significant acoustic changes other than a longer transition duration. Kinematic adjustments were sufficient to maintain overall similar acoustic output before and after bite block insertion.

Keywords: articulatory kinematics, bite block, perturbation, compensation, diphthong

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DESCRIPTION OF THESIS STRUCTURE

This thesis, *Articulatory Kinematic Compensation for a Bite Block During Diphthong Production,* is written in a hybrid format which combines traditional thesis requirements with communication disorders journal publication formats. The preliminary pages of this thesis reflect requirements for submission to the university. The thesis report is presented as a journal article and conforms to length and style requirements for submitting research reports to education journals. The annotated bibliography is found in Appendix A, the informed consent form information is found in Appendix B, and the stimulus phrases in Appendix C.

Introduction

Speech is an intricate and highly skilled human behavior. Evidence in the literature suggests that muscle activity across the components of the speech production mechanism is highly coordinated. Correct production of speech sounds requires the accurate management of speed, force, and timing. Because of the complexity required in speech, disturbances to the speech production system, even seemingly small ones, can make a significant difference in speech output (Brunner et al., 2011; Flege, Fletcher, & Homiedan, 1988).

Perturbation

A perturbation introduces a change to the function of a system. A perturbation can be caused through a device or object placed into the oral cavity which disrupts the normal movement of the articulators, thereby possibly affecting speech production. There are two main types of perturbation: static and dynamic.

Static perturbation exists when the object or device placed into the oral cavity remains stable and consistent in size and shape throughout all utterances. This is the most commonly used type of perturbation in research studies because it requires minimal equipment, making it easily available. Bite blocks, which are small objects placed between the molars, have been used in research on static perturbation. These bite blocks stabilize the jaw while speaking (Fowler & Turvey, 1980). Because natural jaw movements are prevented, the movement of the lips and tongue may adjust to compensate for the lack of jaw contribution. By using the tongue and lips to compensate for the jaw, speakers can maintain near typical speech. However, individual speakers may utilize the tongue and lips in different ways to achieve a similar speech outcome. This idea of using different articulatory movements to achieve the same acoustic output is known as *motor* *equivalence*. In perturbed speech, motor equivalence strategies are often used because the speaker cannot produce speech using their typical methods (Brunner et al., 2011).

Dynamic perturbation occurs when articulation is modified by a device or object that interferes with the movement of the articulators (e.g., applying a sudden horizontal force to the jaw or an unexpected load to the lower lip). The level of interference may change throughout an utterance and is not a stable, consistent perturbation. While most instances of dynamic perturbation would only occur in laboratory experiments, there has been some research involving more naturalistic forms of dynamic perturbation. Mayer, Gick, and Ferch (2009) performed a study of dynamic perturbation in which chewing gum was used as the perturbing object during speech. Chewing is viewed as an articulatory perturbation that is naturalistic, changes over time, and requires constant adjustment. The study found that while the gum bolus interfered with the shapes and movements of the articulators during speech, the relative acoustic distance between the two target phonemes, /s/ and /ʃ/, was maintained. When a dynamic perturbation is introduced, speakers will adjust their strategies to maintain the overall acoustic goal.

Perturbation has been used as a research tool for decades to better understand how speakers adapt to a change in the functioning of the system. Understanding how and when these adaptations occur is helpful not only in basic research, but it could also benefit disordered populations. Brain injury or disease can affect the neural functioning of an individual to the point where speech pathways are disrupted, and the articulators do not move in a typical manner. Due to the damage, the individual cannot implement typical motor strategies. Alternate strategies must be used to compensate for the perturbed system.

Compensatory strategies that speakers use in the presence of a perturbation can vary significantly between individuals. Studies have shown the effects of a variety of devices (e.g., retainers, palatal expanders) on speech sound production (Kulak Kayikci, Akan, Ciger, & Ozkan, 2012; Thibeault, Menard, Baum, Richard, & McFarland, 2011). Thibeault et al. (2011) used thick and thin artificial palates to examine articulatory and acoustic adaptation to palatal perturbation. The study found that not only were fricatives more significantly affected than stops by the perturbation, there was also a large standard deviation between subjects for acoustic center of gravity measurements. While six of the speakers increased center of gravity, three of the speakers decreased their center of gravity. Since all speakers produced speech in similar conditions during the study, these variations likely occurred because the speakers used different strategies to adapt to the perturbation.

Adaptation

Adaptation, or the process of adjusting to new or changing conditions, is a key component of perturbation studies. McFarland and Baum (1995) described the ability to adapt to a perturbation as “a developing system in which a new set of articulatory programs evolves for the change in oral function” (p. 1866). Adaptation is necessary when articulatory mechanisms can no longer achieve adequate speech goals. Research studies involving perturbation have observed speakers’ processes of adapting to the presence of a perturbation.

Results from Jacks (2008) revealed that compensation to a bite block during speech was not complete, either in healthy speakers or in individuals with apraxia of speech. According to McFarland and Baum (1995), consonants required more time to adapt than vowels, and the time required for adaptation varied with each speaker. One study found significant differences in the production of phonemes /s/ and /t/ produced with and without a bite block, further supporting the notion that adaptation to a bite block was neither immediate nor complete (Flege et al., 1988). However, while adaptation may be incomplete when a perturbation is introduced, the extent to which it does occur is enough to adequately preserve intelligibility. Flege et al. (1988) performed perceptual and acoustic analysis on one of the five participants in their study. While the participant displayed significant kinematic changes in the production of /s/ and /t/ during adaptation to a bite block, he maintained near normal speech according to perceptual ratings. Despite the disturbance to the movements of the articulators, the speech goals were still achieved.

Types of Measurement

Acoustic, perceptual, and kinematic measures of speech are sources of data that provide valuable information in research studies involving perturbation. Acoustic data detect differences in before and after insertion of the bite block through measures of formant frequencies, which can reflect vowel accuracy and distinctiveness. Perceptual data from a listener's judgments can determine the extent to which a bite block affects speech and if the listener can discern improvements in speech as compensation occurs. However, acoustic and perceptual measures do not directly quantify articulatory adjustments such as increased tongue raising or lip rounding. These changes can be documented through kinematic measures, a third type of measurement that provides the increased depth and sensitivity necessary to understand the extent of physical adaptation that occurs in the presence of a bite block or other perturbation. Kinematic studies are, however, more expensive, time consuming, and invasive than acoustic or perceptual approaches.

Jacks (2008) used acoustic and perceptual data to determine the effect of a bite block on the speech of individuals with apraxia of speech. Acoustic measures included examining the effect of the bite block on vowel formant frequencies. Listener ratings of the participants' vowel productions were used to determine vowel accuracy and distinctiveness. These measurements revealed that while speakers with apraxia produced vowels with formant frequencies clearly separated in the vowel space, listeners detected differences in the perceptual quality of vowels when compared to typical speakers. However, while acoustic and perceptual measures held value in this study, they did not reveal differences in bite block adaptations between the two speaker groups.

Kinematic measures provide valuable information beyond what acoustic and perceptual data may reveal by directly quantifying articulatory movements and identifying exactly where in space the articulators are. This makes kinematics especially applicable to perturbation studies because of the articulatory adjustments made when adapting to a perturbation. Thibeault et al. (2011) used kinematic measures to observe articulatory changes during adaptation to a palatal perturbation. Although all consonants were impacted by the perturbation to some degree, /s/ revealed the greatest effects. While thick and thin palates had minimal effect on acoustic measures of /s/, the kinematic findings were highly influenced by palatal thickness. The jaw was lower and the tongue moved farther backwards and downwards with the thick palate as compared to the thin palate. Thibeault et al. suggested, “Acoustic measurements were not sensitive enough to capture the differential effects of the thick and thin palates” (p. 2117). The kinematic measures compensated for this lack of sensitivity and revealed details of adaptation to a perturbation that other types of measures could not.

American English Diphthongs

Distinct acoustic patterns and articulatory movements are hallmarks of diphthongs. A diphthong is produced as one vowel sound transitions to another within the same syllable. Diphthongs are often of interest in kinematic studies because of the movement involved as the tongue, lips, and jaw coordinate in complex ways to shift smoothly from one sound to the next. For example, in the diphthong /ɑɪ/, the tongue body lowers to produce /ɑ/ and then rises as it shifts to produce /ɪ/. Because the tongue is anatomically coupled with the jaw (Mefferd, 2017) some jaw movement is inevitable when the tongue moves. The diphthong /ɑʊ/ involves jaw displacement and also incorporates lip rounding as it transitions from /ɑ/ to /u/.

Kinematic measures of diphthongs have an important connection to acoustic measures. Acoustic analysis of diphthongs frequently involves the observation of formant transitions, or the movement of a formant from one vocalic target to another. The first two formants contribute the most to diphthong identification. The movement of the second formant (F2) is most prominent, and the rate of change for F2 transitions varies from diphthong to diphthong (Gay, 1968). Measuring these formant frequencies is useful because it offers information on the movement of the articulators. Lee (2014) found that F1 and F2 in the diphthong /ɑɪ/ were highly predictive of kinematic measures.

A study by Tasko and Greilick (2010) investigated how clear speech affects acoustic and orofacial kinematic measures associated with production of the diphthong /ɑɪ/. Acoustic measures included estimations of F1 and F2 histories, which were used to determine the onset and offset frequencies, duration, extent, and rate of F1 and F2 transitions within the diphthong. Analysis of the acoustic measurements revealed that F1 frequencies significantly increased in the clear condition at transition onset but not at transition offset; F2, on the other hand, showed no clarity-related differences at transition onset but significantly increased at transition offset. Articulatory kinematic measures tracked the motion of two flesh-points on the tongue (T2 and T3) and a single flesh-point on the mandibular incisor (MI). The results of this study revealed that when the speakers altered their speech to be clearer, their articulatory movements changed. Analysis of the flesh-point movements indicated that each articulator showed marked, though individually unique adjustments at movement onset and offset during the clear speech condition.

Additionally, the speakers produced larger and longer articulatory movements in the clear speech condition as compared to conversational speech. Based on these results, it was anticipated that the current study, which also imposes a change to typical speech conditions, would reveal that speakers adjust their articulatory movements to compensate for the altered condition.

While perturbation studies have frequently chosen the tongue and jaw as the main articulators of interest (Flege et al., 1988; Thibeault et al., 2011), analysis of lip contribution is also important, especially in phonemes that involve lip rounding. McKell (2016) found that "lip movements in /aʊ/ were overall more predictive of formant changes than the tongue movements were" (p. 26) during diphthong transitions Not only does the analysis of lip movements contribute to our interpretation of acoustic measures, but these movements themselves are also significant in kinematic studies. Because the lower lip is attached to the jaw, any movement of the jaw will impact lower lip movement. Observations of lip movements during speech with a stabilized jaw revealed that the lower lip compensated with increased movements in order to achieve oral closure, which was sufficient for the accurate production of bilabials (Perkell, Matthies, Svirsky, & Jordan, 1993).

The movements of the tongue, jaw, and lips during diphthong production make diphthongs an optimal candidate for perturbation research. A study conducted by Kelso, Tuller, Vatikiotis-Bateson, and Fowler (1984) examining perturbation observed that the tongue compensated when jaw movements were blocked. As a result, the speaker could still produce nearly normal speech by creating constriction sizes that are similar to those found in unperturbed speech. Similarly, it was anticipated in the present study that restricting jaw movement during diphthong production would result in increased lip and tongue movements.

While previous studies have provided information on the impact of a bite block on vowel and consonant production (Flege et al., 1988; McFarland & Baum, 1995), comparatively little is known about the effect of a bite block on diphthong production. Diphthongs differ from vowels in that articulation for vowels produced in isolation remains relatively static, while the articulation of diphthongs always involves movement during their production. This particular characteristic of diphthongs makes them suitable for studies that may add to the existing literature on the effect of bite blocks as a form of perturbation.

Aims of the Study

The current study used kinematic measures to explore the ways in which individuals changed articulatory movements when a perturbation in the form of a bite block was introduced. Because the jaw is anatomically attached to the tongue and lower lip, movements of each of those articulators will have an effect on the others. It was hypothesized that stabilizing the jaw through the introduction of a bite block would result in increased compensation by the tongue and lower lip during production of diphthongs. We also investigated whether or not the larger movements of the tongue and lower lip were sufficient to overcome the missing contributions of the jaw and if the bite block diphthong was acoustically similar to the diphthong produced before the block was inserted.

Method

Participants

The study involved 20 individuals with no history of speech, language, or hearing disorders. Ten women and 10 men were recruited by word of mouth, and each signed a consent form, which had been approved by the Brigham Young University Institutional Review Board. The mean age of female participants was 24.3 with a standard deviation of 1.2 years. The mean age of male participants was 25.4 with a standard deviation of 2.1 years. Participants received $10 in compensation for their time.

Instrumentation

Each participant was seated in a single-walled sound booth 30 cm from a condenser microphone (AKG C2000B) during recordings. A calibration tone was recorded in the microphone channel to allow for measurement of speech intensity in dB SPL at 50 cm. The articulatory movements were recorded with an NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada). Eight channels of kinematic data were recorded. The first two came from a reference sensor glued to eyeglass frames without lenses. This served as the origin of the coordinate system that was used to measure articulator movements while correcting for head movements. Six channels of articulator data were collected by attaching 3 mm sensor coils at midline to the following structures: three sensors on the tongue (i.e., tongue back (TB), tongue mid (TM) and tongue front (TF), mandibular central incisors used to measure jaw movement (J), vermillion border of the lower lip (LL), and vermillion border of the upper lip (UL). Each coil was attached with cyanoacrylate adhesive. Sensor J was attached to a small square of Stomahesive placed on the teeth to protect the enamel. The sensors tracked the x, y and z positions of the articulators, which were recorded on a computer located outside the sound booth using the Wavefront system. The movement data were gathered at a rate of 100 Hz and the audio signal was recorded at a sampling rate of 22050 Hz.

Bite blocks were made using a silicone impression material (Express STD putty). A small zip tie held the putty in place while it hardened and assisted with the removal of the block after the study. The bite blocks were created bilaterally between the molars with an inter-incisal gap of 10 mm. The size of the bite blocks differed across speakers in order to maintain a consistent distance between the incisors for each participant. Tongue depressors were cut into 10 mm pieces and placed in between the incisors in order to create the 10 mm inter-incisal gap for each participant and to hold this position as the impression material cured.

Speech Stimuli

The vocalic targets were produced as part of the sentence *I'm an owl that hoots*. These included the words *I'm* (diphthong /ɑɪ/), *owl* (diphthong /ɑʊ/), and *hoots* (vowel /u/). The target sentence was part of a larger stimulus set, which was repeated five times. The experimenter modeled the task and the participant was instructed to say the complete sentences with a breath between each repetition.

Procedure

Each participant produced the speech stimuli prior to the sensors being glued to the articulators to allow acoustic recordings of typical speech. An intensity calibration recording was then made using a sound level meter, Extech 407736, with the participant saying /ɑ/ for 5 seconds. The calibration recording was used as a reference level for the remaining speech recordings. After the sensors were attached, and at 2-minute intervals during the following six minutes, additional recordings were made to track the process of adaptation to the presence of the sensors. Between these recordings, the participants engaged in continuous conversation to help them adapt to the presence of the sensors. At the 6-minute mark, the participants produced the speech stimuli once again to gather data before the bite block was inserted. Immediately after the bite block was inserted, the participants produced the speech stimuli at 2-minute intervals during the next six minutes with the bite block still in place while the data were recorded. Immediately after the bite block was removed and the sensors were kept in place, the participants produced the speech stimuli to observe the process of decompensation to the bite block.

The focus of the present study was on the speech stimuli produced immediately prior to bite block insertion (pre-BBI) and immediately after the bite block was inserted (post-BBI).

Kinematic Analysis

A custom Matlab application was created to segment the longer recordings into the individual sentence productions. An additional custom Matlab application was created to further segment the sentence recordings to analyze the transition of the individual diphthongs within the sentence. This application extracted measures of the tongue and jaw displacements by measuring the acoustics changes in the first two formants and the articulator position changes during the transition from the onset to the offset. The relative contributions of the jaw and tongue were computed by decoupling their movements.

This decoupling required an estimation of the vertical movement of the jaw at each sensor location, given the rotational movement of the mandible. Since jaw movement was recorded from a sensor on the lower incisors, the distance of each sensor from the temporomandibular joint (TMJ) was estimated as follows. Earlier work on jaw decoupling (Westbury, Lindstrom, & McClean, 2002) has used an estimate of 110 mm as the average distance from the TMJ to the lower incisors in adults. The present analysis extracted the tongue sensor positions from the kinematic recording of the sustained vowel during the dB calibration. The jaw's contribution to each tongue sensor's vertical displacement was estimated by taking the distance from the TMJ to the sensor and dividing this by the 110 TMJ to incisor sensor distance, then using this factor to compute the jaw's contribution to the horizontal and vertical tongue movements by scaling the incisor sensor's vertical movements accordingly. Horizontal movements of the jaw at each sensor location were directly measured from the incisor sensor's kinematic record, since they were the same on account of the rigidity of the mandible.

Acoustic Analysis

The custom Matlab application used for segmenting the sentence recordings into the individual diphthongs generated audio and kinematic files for /ɑɪ/ and /ɑʊ/. The audio files were then analyzed using Praat 6.0.43 to extract the formant records for F1 and F2. The formant settings in Praat were for a maximum formant frequency of 5500 Hz, measuring five formants with a window length of .025 seconds and a dynamic range of 30 dB. An additional custom Matlab application processed the formant listings from Praat to compute the transition extent in Hz, the transition rate in Hz/s, and the diphthong duration in ms.

Statistical Analysis

The means and standard deviations of tongue marker distance in mm (tongue back, middle, front), jaw contribution to tongue movement in mm, tongue movement independent from the jaw (decoupled) in mm, and the maximum speed of tongue movement in mm/s were calculated in the pre-BBI and post-BBI conditions during production of the diphthongs /ɑɪ/ and /ɑʊ/ by taking the average across five phrase repetitions. A repeated measures analysis of variance (ANOVA) tested the within-subject effects for the differences in each variable after bite block insertion. The data from the female participant F9 and the male participant M5 were removed from statistical analysis due to tracking errors during data collection. Additionally, the number of available data points for each subject varied due to sensor tracking errors or occasional unusual articulatory movements, which is reflected in the degrees of freedom for each

ANOVA. The significance level used throughout analysis was $p < .05$. All statistical analysis was completed with SPSS (v25).

Results

The current study aimed to quantify the articulatory and acoustic changes during production of the diphthongs /ɑɪ/ and /ɑʊ/ that resulted from the insertion of a bite block. Results for the two diphthongs are reported separately. The descriptive statistics are reported in Tables 1, 2, 4, and 5. The results of the repeated measures ANOVA tests are reported in Tables 3 and 6.

Diphthong /ɑɪ/

The repeated measures ANOVA revealed significant differences in the tongue back (TB) and tongue mid (TM) movements but not the tongue front (TF) in bite block speech (see Table 3). There was a bite block by gender interaction for the tongue back distance $F(1,14) = 15.049$, $p = .002$, ES .518 (see Figure 1). For the female participants, the TB distance remained the same between pre-BBI and post-BBI conditions, while the TM distance decreased. The TB and TM distances both decreased for the male participants between pre-BBI and post-BBI conditions (see Table 1, Figure 1). No significant bite block by gender interactions were found for TM or TF.

The repeated measures ANOVA tests for maximum speed revealed significant differences in bite block speech for TB and TM (see Table 3). Tongue maximum speed decreased for the TB and TM movements between pre-BBI and post-BBI, especially for the males (see Table 1, Figure 2). There was a bite block by gender interaction for the TB maximum speed $F(1,14) = 13.529$, $p = .002$, ES .491 (see Figure 2). No significant interactions were found for TM or TF.

The jaw contribution to TB, TM, and TF movements decreased significantly between pre-BBI and post-BBI conditions (see Tables 1 and 3). This testing was conducted to confirm the effect of the independent variable of jaw fixation.

The decoupled TF distance increased significantly between pre-BBI and post-BBI conditions (see Tables 1 and 3). There were bite block by gender interactions for TB decoupled distance $F(1,14) = 7.703$, $p = .015$, ES .355 and TM decoupled distance $F(1,14) = 20.773$, $p < .001$, ES .597. For both TB and TM distance, males and females ended at similar points, while males started higher and decreased and females started lower and increased (see Figures 3 and 4).

The repeated measures ANOVA tests for F1 and F2 transition extent and rate did not reveal significant differences between pre-BBI and post-BBI conditions. There was a significant difference in the transition duration, which increased from pre-BBI to post-BBI (see Tables 2 and 3).

Diphthong /ɑʊ/

Repeated measures ANOVA tests revealed significant differences for the TB marker distance (see Table 6). The TB movement increased between the pre-BBI and post-BBI conditions (see Table 4). No significant changes were found for maximum speed (see Table 4, Figure 5) for TB, TM, or TF. However, the ANOVA revealed a between-subjects effect for gender for TF, $F(1,13) = 5.550$, $p = .035$, ES .299, with higher values for males (see Figure 5). No significant gender differences were found for TB or TM.

The jaw contribution to all tongue movements for males and females decreased between pre-BBI and post-BBI conditions for the diphthong /ɑʊ/ (see Table 4). These changes were statistically significant (see Table 6). The decoupled TB, TM, and TF distance all increased significantly between pre-BBI and post-BBI conditions (see Tables 4 and 6). There were no significant bite block by gender interactions or between-subject gender differences.

The repeated measures ANOVA tests for F1 and F2 transition extent and rate did not reveal significant differences between pre-BBI and post-BBI conditions. There was a significant difference in the transition duration, which increased from pre-BBI to post-BBI (see Tables 5 and 6).

Table 1

Means (and Standard Deviations) for the Kinematic Measures for the Diphthong /ɑɪ/ in the pre-BBI and post-BBI Conditions

		pre-BBI		post-BBI		
	Gender	Mean	SD	Mean	SD	N
TB distance	Female	8.3	5.2	8.3	6.1	7
	Male	14.6	6.4	8.2	4.9	9
TM distance	Female	8.6	4.3	7.5	5.4	7
	Male	12.7	5.4	7.8	4.1	9
TF distance	Female	8.0	4.0	8.1	5.7	7
	Male	10.1	4.0	7.5	2.9	9
TB max speed	Female	111.0	41.8	110.8	49.9	7
	Male	175.4	54.2	96.5	41.1	9
TM max speed	Female	123.8	57.0	99.1	42.3	7
	Male	156.9	52.4	93.6	32.3	9
TF max speed	Female	119.2	56.8	123.5	61.0	7
	Male	144.3	48.0	93.6	20.0	9
TB jaw contrib	Female	4.9	2.8	1.4	0.4	7
	Male	4.5	2.9	1.3	0.6	9
TM jaw contrib	Female	5.3	3.1	1.5	0.4	7
	Male	5.0	3.1	1.4	0.6	9
TF jaw contrib	Female	5.6	3.2	1.5	0.4	7
	Male	5.4	3.4	1.5	0.6	9
TB indep dist	Female	3.4	3.3	6.9	5.9	7
	Male	10.1	4.2	6.8	4.7	9
TM indep dist	Female	3.3	2.2	6.0	5.2	7
	Male	7.7	2.8	6.4	3.8	9
TF indep dist	Female	2.4	1.4	6.5	5.5	7
	Male	4.7	1.3	6.0	2.6	9

Note. TB = tongue back; TM = tongue mid; TF = tongue front; distance = marker distance (mm); max speed = maximum marker speed (mm/s); jaw contrib = decoupled jaw contribution to the net movement of the marker (mm); indep distance = marker distance independent (decoupled) from the jaw (mm).

Table 2

Means (and Standard Deviations) for the Acoustic Measures for the Diphthong /aɪ/ in the pre-BBI and post-BBI Conditions

		pre-BBI		post-BBI		
	Gender	Mean	SD	Mean	SD	N
F1 transition	Female	550.9	171.0	658.3	466.9	8
	Male	439.8	163.5	486.0	249.2	9
F2 transition	Female	537.2	263.4	692.4	558.0	8
	Male	463.7	129.5	634.8	313.2	9
F1 rate	Female	4842.4	2323.4	4948.1	4858.4	8
	Male	4016.3	2073.8	3283.5	1504.5	9
F2 rate	Female	4735.9	3020.7	5163.5	5264.9	8
	Male	4054.2	946.1	4179.4	1746.6	9
Transition duration	Female	123.4	36.7	157.2	81.8	8
	Male	116.5	29.4	150.6	35.6	9

Note. transition = diphthong formant transition (Hz); rate = diphthong transition rate (Hz/s). Duration is in ms.

Table 3

Repeated Measures ANOVA Results for the Effect of a Bite Block on the Dependent Measures for the Diphthong /aɪ/

	df	*F*-ratio	*p*	Effect Size
TB distance	1,14	15.338	0.002	0.523
TM distance	1,14	10.357	0.006	0.425
TF distance	1,14	1.427	0.252	0.092
TB max speed	1,14	13.714	0.002	0.495
TM max speed	1,14	12.493	0.003	0.472
TF max speed	1,14	2.427	0.142	0.148
TB jaw contrib	1,14	24.746	0.000	0.639
TM jaw contrib	1,14	24.854	0.000	0.640
TF jaw contrib	1,14	25.341	0.000	0.644
TB indep dist	1,14	0.032	0.862	0.002
TM indep dist	1,14	0.987	0.337	0.066
TF indep dist	1,14	7.955	0.014	0.362
F1 transition	1,15	0.555	0.468	0.036
F2 transition	1,15	2.359	0.145	0.136
F1 rate	1,15	0.101	0.755	0.007
F2 rate	1,15	0.098	0.758	0.007
Transition duration	1,15	11.106	0.005	0.425

Note. TB = tongue back; TM = tongue mid; TF = tongue front; dist = marker distance; max speed = maximum marker speed; jaw contrib = decoupled jaw contribution to the net movement of the marker; indep distance = marker distance independent from the jaw (decoupled); transition = diphthong formant transition; rate = diphthong transition rate.

Table 4

Means (and Standard Deviations) for the Kinematic Measures for the Diphthong /aʊ/ in the pre-BBI and post-BBI Conditions

		Pre-BBI		Post-BBI		
	Gender	Mean	*SD*	Mean	*SD*	N
TB distance	Female	8.4	1.7	10.3	3.6	7
	Male	7.9	3.5	10.5	3.5	8
TM distance	Female	8.7	1.8	10.2	4.2	8
	Male	9.3	4.2	11.0	3.8	8
TF distance	Female	10.8	3.0	11.6	3.4	8
	Male	11.0	5.9	12.8	5.2	8
TB max speed	Female	117.2	52.5	107.2	43.5	7
	Male	127.0	37.8	144.2	46.3	8
TM max speed	Female	118.5	44.5	112.4	39.6	8
	Male	144.8	31.7	135.6	45.8	8
TF max speed	Female	128.6	43.8	140.2	40.6	8
	Male	192.4	42.2	173.3	59.1	7
TB jaw contrib	Female	4.0	2.1	1.2	0.4	7
	Male	3.1	1.6	1.0	0.6	8
TM jaw contrib	Female	4.4	2.3	1.3	0.4	8
	Male	3.5	1.7	1.1	0.6	8
TF jaw contrib	Female	4.7	2.4	1.3	0.4	8
	Male	3.7	2.0	1.1	0.7	7
TB indep dist	Female	4.5	2.6	9.2	3.5	7
	Male	4.8	3.6	9.5	3.9	8
TM indep dist	Female	4.3	2.0	8.9	4.1	8
	Male	5.8	3.9	10.0	4.1	8
TF indep dist	Female	6.1	3.2	10.2	3.2	8
	Male	8.2	4.9	11.6	5.9	7

Note. TB=tongue back; TM=tongue mid; TF=tongue front; distance = marker distance (mm); max speed = maximum marker speed (mm/s); jaw contrib = decoupled jaw contribution to the net movement of the marker (mm); indep distance = marker distance independent (decoupled) from the jaw (mm).

Table 5

Means (and Standard Deviations) for the Acoustic Measures for the Diphthong /aʊ/ in the pre-BBI and post-BBI Conditions

		pre-BBI		post-BBI		
	Gender	Mean	*SD*	Mean	*SD*	N
F1 transition	Female	401.0	108.7	387.1	224.5	9
	Male	269.3	143.8	256.1	115.1	9
F2 transition	Female	429.6	154.2	477.7	259.1	9
	Male	388.3	113.1	374.6	105.1	9
F1 rate	Female	2976.5	1244.5	2144.7	912.1	9
	Male	1837.1	774.4	1763.7	815.2	9
F2 rate	Female	3131.7	1492.2	2733.2	1547.2	9
	Male	2996.8	695.0	2507.7	713.6	9
Transition duration	Female	147.6	48.1	184.7	74.7	9
	Male	132.2	29.3	154.2	35.3	9

Note. transition = diphthong formant transition (Hz); rate = diphthong transition rate (Hz/s). Duration is in ms.

Table 6

Repeated Measures ANOVA Results for the Effect of a Bite Block on the Dependent Measures for the Diphthong /aʊ/

	df	*F*-ratio	*p*	Effect Size
TB distance	1,13	5.198	0.040	0.286
TM distance	1,14	2.029	0.176	0.127
TF distance	1,14	1.331	0.268	0.087
TB max speed	1,13	0.076	0.787	0.006
TM max speed	1,14	0.937	0.350	0.063
TF max speed	1,13	0.088	0.771	0.007
TB jaw contrib	1,13	27.021	0.000	0.675
TM jaw contrib	1,14	32.194	0.000	0.697
TF jaw contrib	1,13	28.777	0.000	0.689
TB indep distance	1,13	20.759	0.001	0.615
TM indep distance	1,14	19.870	0.001	0.587
TF indep distance	1,13	21.481	0.001	0.623
F1 transition	1,16	0.091	0.767	0.006
F2 transition	1,16	0.187	0.671	0.012
F1 rate	1,16	2.297	0.149	0.126
F2 rate	1,16	1.930	0.184	0.108
Trans duration	1,16	14.663	.001	.478

Note. TB=tongue back; TM=tongue mid; TF=tongue front; distance = marker distance; max speed = maximum marker speed; jaw contrib = decoupled jaw contribution to the net movement of the marker; indep distance = marker distance independent from the jaw (decoupled); transition = diphthong formant transition; rate = diphthong transition rate.

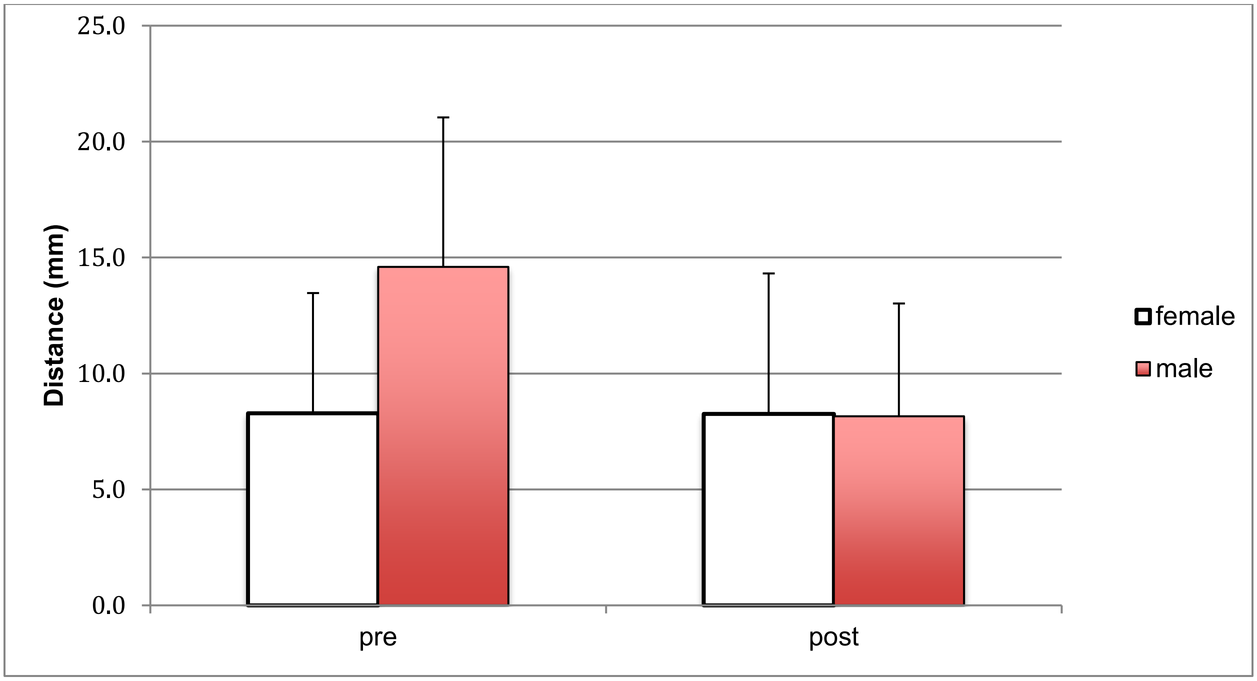

Figure 1. Means (and standard deviations) for male and female tongue back marker distance (mm) in the pre-BBI and post-BBI conditions for the diphthong /ɑɪ/.

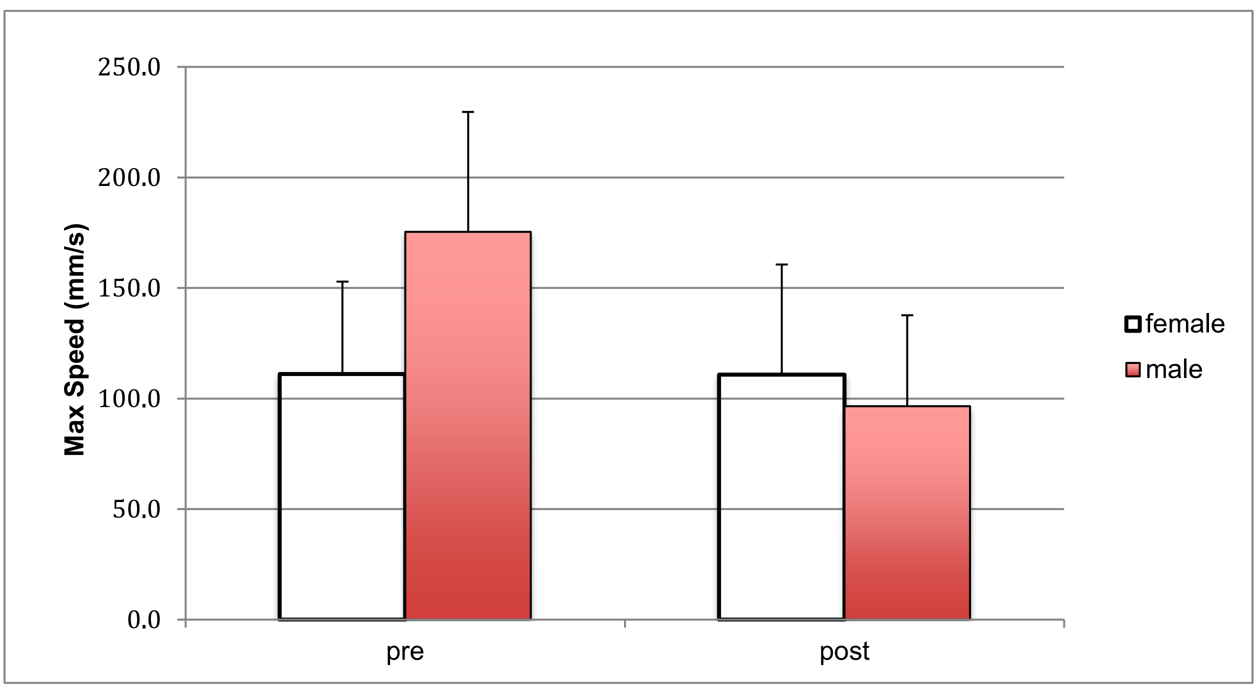

Figure 2. Means (and standard deviations) for male and female tongue back maximum speed (mm/s) in the pre-BBI and post-BBI conditions for the diphthong /ɑɪ/.

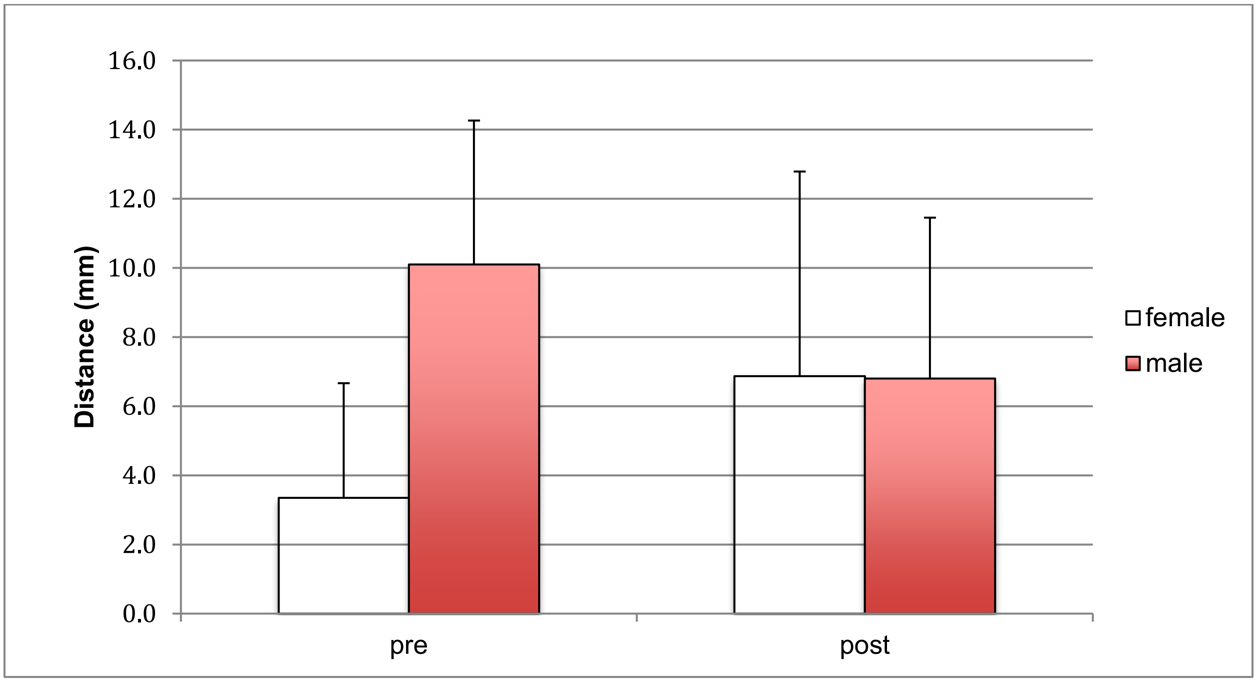

Figure 3. Means (and standard deviations) for male and female tongue back marker distance independent from the jaw (decoupled) in the pre-BBI and post-BBI conditions for the diphthong /ɑɪ/.

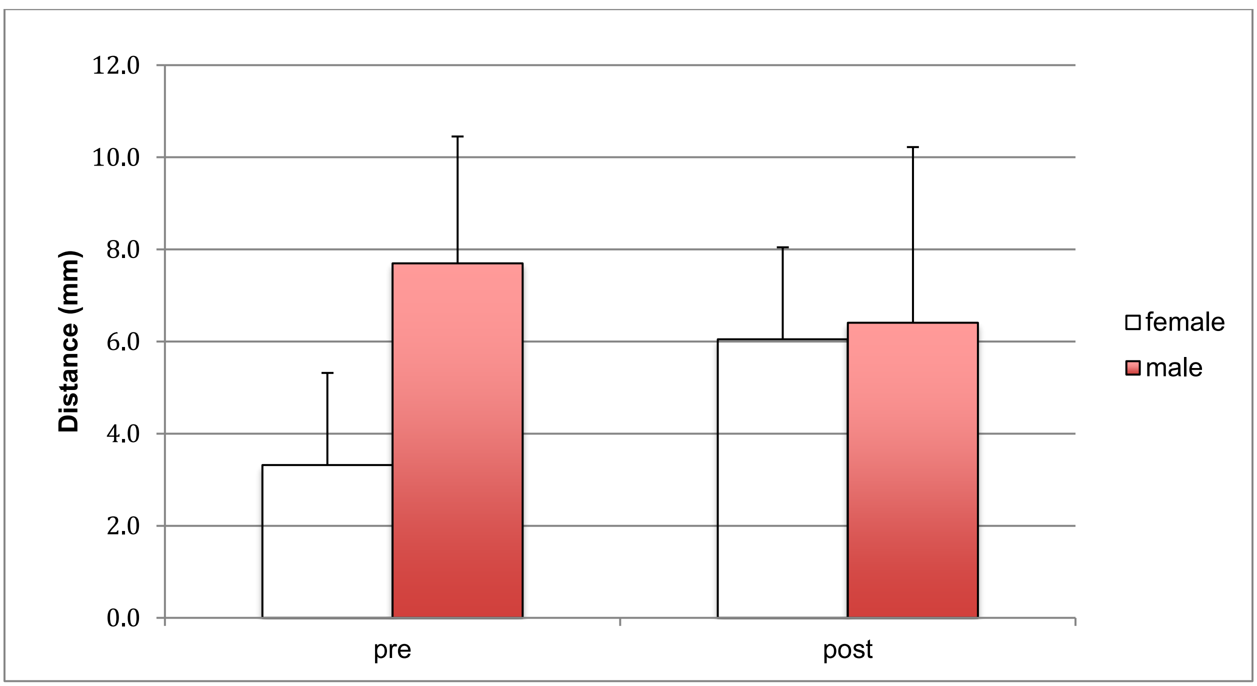

*Figure 4***.** Means (and standard deviations) for male and female tongue mid marker distance independent from the jaw (decoupled) in the pre-BBI and post-BBI conditions for the diphthong /ɑɪ/.

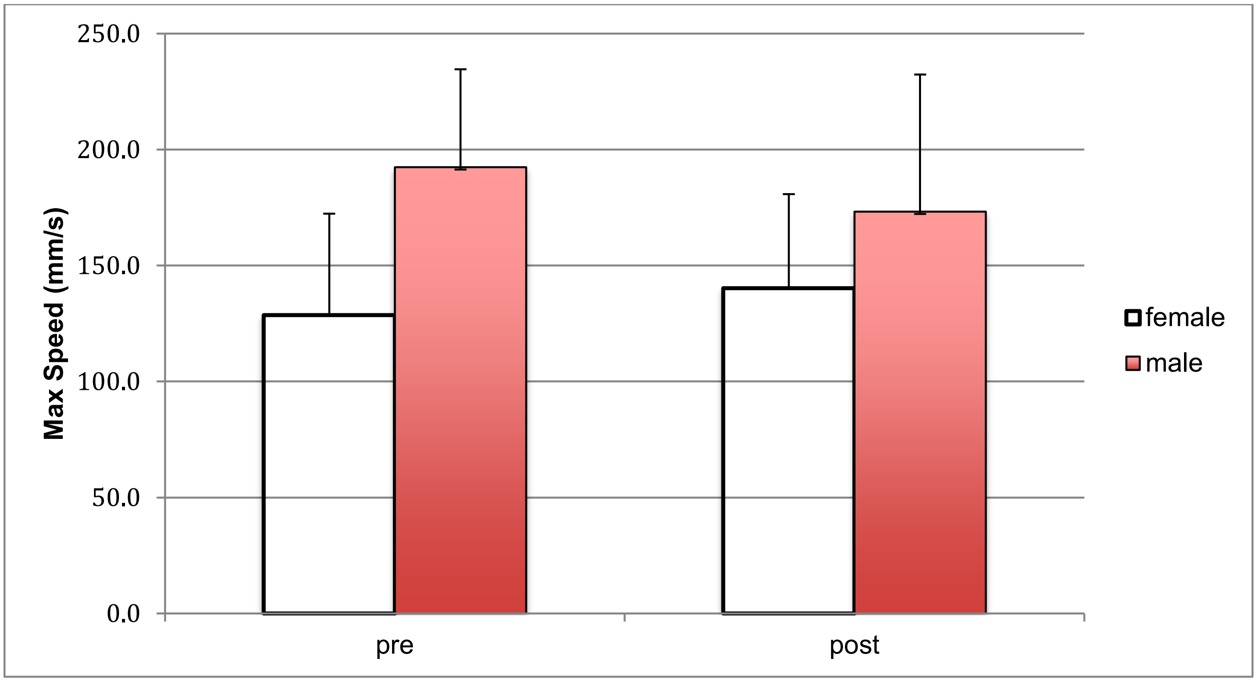

Figure 5. Means (and standard deviations) for male and female tongue front maximum speed (mm/s) in the pre-BBI and post-BBI conditions for the diphthong /ɑʊ/.

Discussion

This study examined kinematic and acoustic changes in diphthong production following the insertion of a bite block. While there were no acoustic changes, kinematic changes were observed as speakers adjusted their articulation to compensate for the bite block. These findings reveal that speakers maintained the acoustic features of the diphthongs by adjusting their articulatory patterns when the jaw's typical contribution was removed.

Kinematic Compensation

As expected, there were significant changes in the movements of the tongue markers, especially when considering the decoupled tongue movements after the bite block insertion.

Thibeault et al. (2011) examined kinematic compensation to the presence of a palatal perturbation during the production of consonants. All consonants were affected by the presence of the perturbation, with /s/ being affected the most. When a thick palatal perturbation was introduced, the jaw moved lower and the tongue moved further backwards and downwards during /s/ production. The significant compensatory adjustments observed in this study led the researchers to conclude that although the impact of a palatal perturbation is complex, the speech production system is highly flexible, and compensation can be observed immediately. This finding was consistent with the findings of the present study. Although the studies differ in the type of perturbation and speech targets used for analysis (consonants vs. diphthongs), both revealed that in the presence of a perturbation, speakers make kinematic adjustments to compensate.

These observations imply an important contribution of sensory feedback in making motor performance adjustments, which is consistent with previous research. Flege et al. (1988) suggested that during adaptation to a bite block, speakers used sensory feedback to provide error-based correction. They also suggested that particular sound classes that may require greater articulatory precision, such as sibilants, rely more heavily on feedback, especially under conditions of articulatory perturbation. McFarland and Baum (1995) supported the notion that sensory feedback contributes to articulatory changes in their study of compensation and adaptation to the presence of a bite block. They also concluded "adaptation to articulatory perturbation may be viewed as a developing system in which a new set of articulatory programs evolves for the change in oral function" (p. 1866).

To the best of our knowledge, there have not been any studies that have explored the kinematic effects of a bite block on diphthong production. However, previous research has investigated diphthong production in altered conditions, such as clear speech. A study by Tasko and Greilick (2010) showed that clear speech has a significant kinematic effect on the production of /ɑɪ/. The researchers tracked the motion of two flesh-points on the tongue and a single flesh-point on the mandibular incisor. Analysis of the articulatory movements during the clear speech condition revealed marked, though individually unique, articulatory adjustments at movement onset and offset. All three sensors began the articulatory transition at a lower position and both tongue sensors were higher and more anterior at the transition offset during the clear speech condition. Articulatory movements were also larger and longer in duration in the clear speech condition.

The altered speaking condition in the present study also led to articulatory adjustments by the tongue. During production of /ɑɪ/, the TB and TM markers showed significant changes when the bite block was inserted. There was a significant decrease in TB distance, and Table 1 and Figure 1 show that the males accounted for this difference. The TM distance revealed similar results. For males, the TB and TM distance and maximum speed decreased. For females, TM decreased in distance and TB decreased in distance and speed. During the diphthong /ɑʊ/, TB movements increased significantly, while there were no significant changes for maximum speed for any tongue marker.

A study by Kelso et al. (1984) also found that the articulators, especially the tongue, compensated for the presence of a perturbation. For the production of both /b/ and /z/ with a fixed jaw, “highly amplified tongue-muscle activity” (p. 829) was observed and contributed to near-normal speech output. The current study found a similar pattern of increased tongue movement to compensate for the bite block. Analysis of tongue movements independent (decoupled) from the jaw revealed a significant increase for TB, TM, and TF distance during the diphthong /ɑʊ/. However, while increased tongue movement was observed for the tongue markers during the diphthong /ɑʊ/, decoupled TF distance actually decreased significantly during production of the diphthong /ɑɪ/. This could be explained by the location of /ɑɪ/ in the carrier phrase. Because it was produced at the very beginning of the target phrase, the articulators may not have uniformly followed the anticipated trajectory. The positioning of the articulators prior to the onset of the phrase was not constrained by the phonetic context, which may have led to inconsistencies in lingual articulation.

While the tongue overall showed evidence of compensation between pre-BBI and post-BBI conditions, only two of the three individual tongue distance markers (TB and TM) showed significant differences. This may have been related to the distance of each tongue marker from the point of lingual attachment to the jaw. Because the TB marker was located on the tongue close to its biomechanical attachment to the jaw, it had less flexibility in moving independently when the jaw was fixed. On the other hand, the TF, being further from the point of attachment to the jaw, still had the ability to move freely and make similar movements in both the pre-BBI and the post-BBI conditions.

Analysis of TB distance and TB maximum speed for the diphthong /ɑɪ/ revealed a bite block by gender interaction, indicating that the bite block had a different effect for men and women. Distance marker values for TB and maximum speed values for TM were similar for males and females in the post-BBI condition, but males began the pre-BBI condition with much larger values than females.

There was also a between-subjects effect for gender for TF maximum speed during production of the diphthong /ɑʊ/, revealing that overall, men made faster movements than women for TF. This could be because men generally have larger tongues than women and thus can make both larger and faster movements.

Acoustic Compensation

Acoustically, transition rates and extents did not change for F1 and F2 when the bite block was inserted. However, there was a significant difference in the transition duration for both /ɑɪ/ and /ɑʊ/, which increased from pre-BBI to post-BBI. It was reasoned that the transition duration could increase because the articulators made larger movements due to the need to maintain diphthong accuracy in the presence of a large inter-incisal gap. The decoupled TB, TM, and TF markers all increased significantly in distance between pre-BBI and post-BBI conditions for /ɑʊ/. These larger movements of the tongue likely took longer to produce, thus increasing the time required for the formants to transition from the diphthong onglide to offglide.

Nonsignificant changes in F1 and F2 with a bite block are consistent with previous perturbation studies. Thibeault et al. (2011) found that while there were significant kinematic changes for consonant production, overall acoustics did not change significantly. Articulatory movements for /s/ production were highly influenced by palatal thickness while /s/ acoustics were minimally affected. These results likely indicate that the speakers were able to compensate their articulatory movements in the post-BBI condition enough to achieve an overall similar acoustic output to the pre-BBI condition.

Limitations of the Current Study and Directions for Future Research

The analysis of the stimulus phrases in the present study resulted in some challenges in segmentation, especially for the diphthong /ɑɪ/. Because /ɑɪ/ was spoken at the beginning of the target phrase *I'm an owl that hoots*, some of the participants did not produce /ɑɪ/ in the anticipated manner (low to high, back to front). In some cases the tongue movements started at high front, came down, and went back up to end at high front. Having similar start and end points resulted in the analysis showing much less overall tongue movement than there actually was during that particular diphthong. This problem could have been avoided by embedding the diphthongs in the middle of a word rather than at the beginning of a phrase. Because the diphthong /ɑɪ/ began the phrase, the speakers could have initiated the movement for the diphthong from a range of articulatory positions.

An unanticipated limitation was discovered when analyzing these data for changes in articulatory movements from pre-BBI and post-BBI conditions. Some participants inconsistently bit down on the bite block, and this varied token by token. The amount of jaw stabilization was therefore irregular throughout data collection for these speakers. Further studies could overcome this limitation by providing more explicit instructions to the speakers to remind them to keep the blocks firmly held between the molars and to not allow the jaw to loosen during speech production.

Another limitation of the current study was a smaller number of participants than initially anticipated. Due to tracking errors of some sensors during data collection, two participants' data could not be used for analysis. As a result, there were fewer than 20 participants, slightly lowering the statistical power. Additionally, some of the tokens where the participants did not keep bite blocks firmly in place or had unusual articulatory movements had to be excluded from analysis of the kinematic results. This resulted in fewer than five tokens to average for those participants. The current study gathered data regarding the initial response to a perturbation. Future analysis of this data set could explore the adaptation over time to the presence of a bite block.

Conclusion

This study examined the kinematic and acoustic changes in diphthong production following the insertion of a bite block. Speakers were able to maintain similar acoustic output as they adjusted kinematically to allow for this. This provides further evidence that the speech motor control system is highly adaptable in the presence of a perturbation.

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APPENDIX A

Annotated Bibliography

Brunner, J., Ghosh, S., Hoole, P., Matthies, M., Tiede, M., & Perkell, J. (2011). The influence of auditory acuity on acoustic variability and the use of motor equivalence during adaptation to a perturbation. *Journal of Speech, Language, and Hearing Research, 54*, 727-739. doi: 10.1044/1092-4388(2010/09-0256)

Objective: The purpose of this study was to explore the relationship between speakers' auditory acuity for sibilant contrasts, their use of motor equivalence in producing the sibilant /sh/, and the acoustic distance between sibilants /s/ and /ʃ/ that they produced. Specifically, the study was designed to test the hypothesis that, during perturbation to the vocal tract shape, speakers with high acuity use motor equivalence strategies more than individuals with low acuity and that those with high acuity also produce greater acoustic distance between two sibilant phonemes.
Method: Subjects included seven German speakers between the ages of 25 and 56 with no history of significant speech or hearing problems. Artificial palates were used to perturb the speech and the speakers were instructed to wear them often for a period of two weeks. Electromagnetic articulography recorded the speakers as they produced the sibilants in a carrier phrase with the artificial palates in place. Acoustic distance was calculated between /s/ and /ʃ/. Auditory acuity was measured using labeling and discrimination tests.
Results: Speakers with high acuity employed motor equivalence strategies to a greater degree than speakers with lower acuity when adapting to a perturbation. Additionally, slow speakers used motor equivalence strategies less than fast speakers.
Conclusion: The study confirmed the hypothesis that speakers with high auditory acuity use motor equivalence more and produce clearer phonemic contrasts. Motor equivalence also plays a larger role in the presence of perturbation.
Relevance to the Current Work: This study explores how motor equivalence plays into the production of sibilants in the presence of perturbation. Perturbation increases motor equivalence, meaning the speakers' articulation changed in order to produce the same sound as before the perturbation was introduced. The current study also explores perturbation and its effect on articulation.

Flege, J. E., Fletcher, S. G., & Homiedan, A. (1988). Compensating for a bite block in /s/ and /t/ production: Palatographic, acoustic, and perceptual data. *Journal of the Acoustical Society of America*, *83*, 212-228. doi: 10.1121/1.396424

Objective: This study observed linguapalatal patterns in the phonemes /s/ and /t/ produced normally and with a bite block to help determine which articulatory characteristics are essential for the phoneme's correct identification and which are not.
Method: The participants in the study were two male native speakers of English between the ages of 19 and 21 and three native speakers of Arabic. Phonetically similar English and Arabic words containing the target phonemes were embedded into the carrier phrase "Say to me — again." The speakers were unaware that /s/ and /t/ were the phonemes being analyzed. An acrylic bite block with indentations for tooth cusps was used to stabilize the jaw and create an 8-15 mm vertical distance between the central incisors during sustained productions of /s/. The participants

wore a pseudopalate with 64 sensors attached during data collection. To allow for adaptation while the bite block was in place, the speakers conversed with the experimenter for a 10-minute interval between data collection sets.
Results: Three of the speakers contacted fewer sensors during /s/ production with the bite block in place than without while the other two contacted more post-bite block than normal samples. The bite block affected the width of the groove during /s/ production in the Arabic speakers but not in the English speakers. English speakers compensated better to the presence of the bite block than the Arabic speakers. All five speakers formed a groove for /s/ in the second bite block sample but two speakers did not produce /t/ with complete constriction. Some speakers improved their speech after a period of adaptation to the bite block during conversation while others showed a decrease in speech quality during the second bite block sample.
Conclusions: The results suggest that a groove is critical for /s/ but complete constriction is not necessary for /t/. The mixed results of speech quality in the second bite block sample suggest that some speakers may have overcompensated to the presence of a bite block while others did not. This supports the notion that adaptation to a bite block is not instantaneous or complete.
Relevance to Current Work: This study examined the effects of a bite block on consonant production. The current study examines the effects of a bite block on diphthong production.

Fowler, C. A., & Turvey, M. T. (1980). Immediate compensation in bite-block speech. *Phonetica, 37*, 306-326. doi:10.1159/000260000

Objective: The aim of this study was to determine the ability of people who stutter (PWS) to use sensory information for motor control based on immediate compensation and adaptive changes in response to a bite block across different speech rates.
Method: Five men who stutter and five men who do not stutter participated in the study. The PWS were rated for severity and received ratings ranging from mild to severe. Stimuli consisted of nonword syllable combinations and were produced at a normal and then fast rate of speech. Over two separate days, recordings were made using electromagnetic articulography with and without the presence of a bite block with practice time allowed to adjust to the bite block. Kinematic analysis was performed from each recording.
Results: At normal rates without the bite block, PWS upper lip movement amplitudes, peak velocities and duration were greater than the control group. Both PWS and the control group responded similarly in terms of movement patterns to the presence of a bite block at a normal speaking rate. However, at a fast speaking rate, PWS reacted differently to the bite block than the control group. At a fast rate, PWS increased their upper lip movement amplitudes and peak velocities while the control group did not. In the presence of a bite block and at fast speech rates, variability of coordination patterns decreased for both groups.
Conclusions: Results indicated that the bite block did not make it more difficult to control individual articulatory movements in PWS. Instead, it had a stabilizing effect on the speech motor control of both groups.
Relevance to the Current Work: This study analyzed adaptation to the presence of a bite block in both people who stutter and people who do not stutter. The current study analyzes adaptation to the presence of a bite block during diphthong production in typical adults.

Gay, T. (1968). Effect of speaking rate on diphthong formant movements. *Journal of the Acoustical Society of America*, *44*, 1570-1573. doi: 10.1121/1.1911298

Objective: The purpose of this study was to determine the effect that speaking rate has on formant movements of diphthongs. It also aims to identify the effects of consonant context on duration and target-frequency position.
Method: Duration and formant frequency measurements were collected from a list of words recorded in a sentence context. Five young adult males read a list of sentences out loud containing 50 different CVC monosyllables with each diphthong represented 10 times. Each speaker recorded the list at a normal conversation rate, a fast rate, and a slow rate with practice time before each condition.
Results: Onset frequency positions showed no change in any of the duration conditions. First and second formant offsets showed changes in frequency levels for each of the duration conditions. Each diphthong showed a clear change in formant offsets. Second formant offset rate of change for each diphthong remained relatively constant across changes in duration.
Conclusions: The results suggest that two features govern diphthong formant movement: onset frequency position and second formant rate of change. The dipthhongs /ɔɪ, ɑɪ, ɑʊ, ɛɪ, oʊ/ should be treated as unit phonemes rather than a vowel plus semivowel.
Relevance to the Current Work: This study explores the effect of speaking rate on diphthong production. The current study explores the effect of a bite block on diphthong production.

Jacks, A. (2008). Bite block vowel production in apraxia of speech. *Journal of Speech, Language, and Hearing Research, 51*, 898-913. doi:10.1044/1092-4388(2008/066)

Objective: This study was designed to examine adaptation to an articulatory constraint, or bite block, as well as the bite block's effects on vowel production in speakers with acquired apraxia of speech and aphasia.
Method: Participants included five adults with acquired apraxia of speech and aphasia and five healthy control speakers. The participants produced the vowels /i/, /ɛ/, and /ae/ in four word-length conditions with and without a bite block. The vowels and diphthong were analyzed acoustically and perceptually. In addition, vowel accuracy and distinctiveness were determined from idealized vowels based on each person's best performance.
Results: Perceptual and acoustic measures revealed clear separation of vowel formants and impaired vowel production in speakers with apraxia of speech. In addition, both individuals with apraxia of speech and the healthy controls demonstrated incomplete adaptation to the bite block.
Conclusions: Vowel production was less accurate overall in speakers with apraxia of speech than in the healthy controls, but feedback control for vowel production was relatively intact in both groups.
Relevance to the Current Work: This study explored production of vowels with the presence of a bite block in healthy speakers and individuals with apraxia of speech. The current study explores production of diphthongs with the presence of a bite block in healthy speakers.

Kelso, J. A., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(6), 812-832. doi:10.1037/0096-1523.10.6.812

Objective: This study examined the effects of perturbing the jaw during the production of /b/ and /z/ in order to find the relationship between the mandible, tongue and lips.

Method: Three experiments were completed during this study. The subject in Experiment 1 was one adult male who was one of the authors of this study. A speech sample was gathered with two different stimuli, “a /baeb/ again and “a /baez/ again.” Each stimuli was repeated 40 times in a single block with 20% of these trials adding a load of perturbation of first, 1.5 s, and then, 50 ms on the jaw during the closure gesture for the final /b/ and final /z/. The perturbation was a custom-made titanium dental prostheses which was fitted onto the lower teeth with two small rods protruding out from the sides of the mouth. Experiment 2 consisted of the same subject and stimuli. Each stimuli was repeated 40 times in two 20-trial blocks with 25% of the trials adding a load of 5.88 N to the final /b/ and final /z/. The perturbation was a jaw-loading device with electrodes to track the movements of the jaw, upper lip and lower lip. Experiment 3 was carried out to combine the findings of the first two experiments by examining the reactions of the jaw perturbation. Experiment 3 consisted of one adult male subject who was not one of the authors of the study. The stimuli contained two utterances, /baeb/ again and /baep/ again. Each stimuli was repeated 80 times in a single block with 12.5% of the trials being perturbed during the opening of the jaw. The perturbation amount was a force load of 5.88N with a duration of 1.5 s.
Results: Experiment 1 found that the 1.5 s load stopped the jaw from reaching its typical position. The upper-lip downward movement was lower for the final production of /b/ in the perturbed trials than for the unperturbed trials due to the needed adaptation. No difference was found in the position of the upper-lip for the production of /z/. The 50 ms load demonstrated no effect on the position of the jaw or the lower-lip. The upper lip downward movement was lower for the /b/. Experiment 2 also found that the upward jaw movements differed in the loaded and unloaded trials. Even though the jaw movement was prevented, lip closure for /b/ and frication for /z/ were produced for all trials. Experiment 3 found that the perturbation influenced the jaw movement. The jaw rapidly extended downward after the perturbation was initiated and the upper-lip extended downward to produce the bilabials.
Conclusion: The upper lip, lower lip and tongue all responded to the perturbation applied to the jaw in productions of /b/ and /z/. The adaptive reactions observed could be described as reflexive due to their speed. The findings also suggest that the organization of the articulators must be tailored to the specific speech act.
Relevance to the Current Study: The current work examined the effect of static perturbation to speech production. This study also gave insight into dynamic perturbation.

Kulak Kayikci, M. E., Akan, S., Ciger, S., & Ozkan, S. (2012). Effects of Hawley retainers on consonants and formant frequencies of vowels. *Angle Orthodontist*, *82*, 14-21. doi:10.2319/032911-226.1

Objective: The aim of this study was to determine if a Hawley retainer caused speech disturbances and to identify the duration of speech adaptation to the retainer.
Method: The participants included twelve native Turkish adolescents aged 11-18. The participants wore the retainer 24 hours a day for 6 months. Speech sounds were assessed at various points over the course of several months using objective acoustic evaluations of vowels and subjective articulation assessment of consonants.
Results: The articulation assessment revealed statistically significant distortions with /s/ and /z/ consonants. The acoustic analysis results demonstrated no statistically significant difference in formant frequencies for /a/, /e/ or /u/. Significant changes were recorded for /i/, including a decrease in the first three formant frequencies. .

Conclusions: The tongue changes its target position when a perturbation is introduced within the oral cavity. The retainer also changes the shape and length of the vocal tract, which affects vowel quality and resonance frequencies. Adaptation does occur, but it is not immediate or complete.
Relevance to the Current Study: This study observed the effects of a static perturbation in the oral cavity. The findings of this study helped guide the use of perturbation in the current study, which also examines the effects of a static perturbation in the oral cavity.

Lee, J. (2014). Relationship between the first two formant frequencies and tongue positional changes in production of /aɪ/. *Journal of the Acoustical Society of America*, *135*, 2294. doi:10.1121/1.4877541

Objective: The purpose of this study was to examine the relationship between F1 and F2 trajectories and changes in tongue height and advancement during the diphthong /aɪ/.
Method: Ten native speakers of American English participated in the study. They each produced three repetitions of the sentence *I say hide again.* Kinematic analysis was performed using information obtained via coils attached to each speaker's tongue. Audio was recorded simultaneously with the kinematic data.
Results: F1 decreased as the tongue height increased and as the tongue advanced. F2 increased as the tongue advanced and as tongue height increased. F1 and F2 had similar relationships with both x and y movements. These correlations were significant within speakers and across speakers.
Conclusions: F1 and F2 showed the expected relationship to tongue advancement and tongue height.
Relevance to the Current Work: This study provided valuable information on the relationship between acoustic and kinematic measures.

Mayer, C., Gick, B., & Ferch, E. (2009). Talking while chewing: Speaker response to natural perturbation of speech. *Canadian Acoustics, 37*, 144-145. Retrieved from https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2175

Objective: This study explored the acoustic and articulatory effects of chewing during speech.
Method: Seven native English speakers participated in the study. Audio and video recordings were made as the speakers produced the carrier phrase "I'm a ___" followed by one of three words containing the target phonemes: 'saw', 'shaw', or 'raw'. The stimuli were produced in two conditions: while chewing a large bolus of gum, and a no-gum control condition. An ultrasound machine with 180-degree probes was used to record midsagittal images of the tongue. Each speaker wore a pair of sunglasses with two sticks and two pink dots attached to the sunglasses and to the probe, which allowed for correction of head movement. Acoustic center of gravity measurements were made.
Results: Three of the speakers did not display any significant differences in center of gravity between the two conditions. Three of the speakers displayed significant differences while the remaining speaker displayed differences in only some of the target phonemes. For the three speakers who displayed differences, absolute acoustic targets were compromised by the presence of gum while the relative distances between the phonemes remained similar. For all speakers, the presence of a large gum bolus interfered with the shapes and movements of the articulators during speech but the overall acoustic goal was maintained.

Conclusions: These results suggest that speakers in control of their own articulatory perturbations adjust their strategies to maintain the acoustic goals of speech. The speakers modify their chewing strategies and use acoustic feedback to achieve adequate acoustic-auditory targets.
Relevance to the Current Work: This study examined the effects of a natural perturbation of speech while the current study examines the effects of an artificial perturbation of speech.

McFarland, D. H., & Baum, S. R. (1995). Incomplete compensation to articulatory perturbation. *The Journal of the Acoustical Society of America*, *97*, 1865-1873. doi:10.1121/1.412060

Objective: This study examined individual adaptation to the presence of a bite block as well as the role of feedback in developing compensatory strategies.
Method: 15 native French speaking women aged 20-33 with no known speech or language disorders participated in the study. An immediate compensation subtest and a postconversation postconversation subtest were administered to each participant. The immediate compensation subtest consisted of three conditions: normal, small bite block (SBB), and large bite block (LBB). The postconversation subtest consisted of two conditions: normal and small bite block.
Results: Analyses of immediate conversation and postconversation subtest results were based on durational and spectral measures. Duration measures within the immediate compensation subtest demonstrated shorter duration of the production of /s/ within the LBB condition compared to the SBB. Durations of /ʃ/ during the SBB condition were substantially longer than in other conditions. The bite block demonstrated little effect on duration within the postconversation subtest. Spectral measures within the immediate compensation subtest revealed higher F1 and F2 values in the LBB conditions than the SBB or normal conditions. The postconversation subtest did not reveal any significant differences across vowel formants in any of the conditions. For stop and fricatives, the values in the bite block conditions were lower than the normal condition.
Conclusions: The results suggest that adaptation to the presence of a bite block is not immediate. The study also revealed that consonants were also more affected by the perturbation than the vowels. Consonants also require a longer period of adaptation than vowels. Individual differences in compensatory strategies were not consistent.
Relevance to the Current Work: This study observed how a bite block affects speech, including the level of compensation that occurs. These findings were helpful in setting up data collection and provided useful information on bite block use during the current study.

McKell, K. M. (2016). *The association between articulator movement and formant trajectories in diphthongs* (Unpublished master's thesis). Brigham Young University, Provo, Utah.

Objective: This study examined the association between formant trajectories and tongue and lip movements in the diphthongs /aɪ/, /aʊ/, and /ɔɪ/.
Method: Participants included 17 native speakers of American English. Electromagnetic sensors on the tongue and lips were used to collect kinematic data, which were time aligned with the acoustic data. F1 and F2 trajectories of the middle 50% of the diphthong were compared to the kinematic data of the tongue and lips via absolute difference of z-scores along each track.
Results: Tongue movement may be the best predictor of F1 and F2 changes for the diphthong /aɪ/, likely because the diphthong lacks lip rounding. Lip movement may be the best predictor of F1 and F2 changes in the diphthong /aʊ/, likely due to the substantial lip rounding of the offglide

vowel. The action of the lips and tongue during production of the diphthong /ɔɪ/ presented challenges in determining the relationship between the articulators and formant changes.
Conclusions: The articulators that most contribute to F1 and F2 differ based on diphthong. The lips and tongue are both valuable contributors to acoustic and kinematic data.
Relevance to the Current Work: This study provided useful information on the contributions of the tongue and lips during diphthong production.

Mefferd, A. S. (2017). Tongue- and jaw-specific contributions to acoustic vowel contrast changes in the diphthong /ɑɪ/ in response to slow, loud, and clear speech. *Journal of Speech, Language, and Hearing Research, 60,* 3144-3158. doi:10.1044/2017_JSLHR-S-17-0114

Objective: The purpose of this study was to examine jaw and tongue displacement changes and how those changes contributed to acoustic vowel contrast changes during slow, loud, and clear speech.
Method: Twenty English-speaking individuals ranging in age from 18-28 participated in the study. All participants had normal speech, language, and hearing and no neurological conditions. Each speaker repeated the phrase “see a kite again” first with normal speech and then at half their typical speaking rate, twice as loud, and as clearly as possible while using effortful articulation to overenunciate each word. The phrase was repeated five times under each condition. Speech kinematics were recorded using 3-dimensional electromagnetic articulography.
Results: Jaw and tongue displacements significantly increased during the slow, loud, and clear speech conditions. However, jaw displacements increased more during clear speech than during slow and loud speech while tongue displacements increased more during slow speech than during clear and loud speech. Acoustic vowel contrasts were greatest during slow speech and were predominantly tongue-driven whereas contrasts were smallest during loud speech. Differences between slow and clear speech were more pronounced in females than males, which suggests gender-specific interarticulatory performance patterns.
Conclusions: Task-specific patterns of tongue and jaw displacement and tongue and jaw contributions to vowel acoustics change across speech modifications. Though it is currently unknown how tongue and jaw displacements change under various speech conditions in individuals with dysarthria, speech modifications that maximize tongue displacement in impaired talkers may increase acoustic vowel contrast more than those that elicit predominantly jaw displacement changes.
Relevance to the Current Work: This study examined acoustic vowel contrasts in relation to tongue and jaw displacement under various speech conditions using 3-D electromagnetic articulography. The current study examines tongue and jaw adaptations during production of diphthongs in the presence of perturbation using 3-D electromagnetic articulography.

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 Acoustical Society of America, 93*, 2948-2961. doi: 10.1121/1.405814

Objective: This study explores the hypothesis that adjusting two independent articulatory parameters (tongue-body raising and lip rounding) will result in decreased acoustic variability in

production of the vowel /u/. The two parameters should have a negative correlation if the hypothesis is correct.
Method: Four English-speaking males without any pronounced dialect participated in the study. Articulatory and acoustic data were collected using an electromagnetic midsagittal articulometer (EMMA). The speakers were instructed to pronounce 300 short phrases containing the vowel /u/.
Results: Three out of the four speakers showed negative correlations between tongue-body raising and lip rounding, which provides some support for the hypothesis. The fourth showed a positive correlation between tongue-body raising and lip rounding.
Conclusions: The findings provide tentative support for motor equivalence at the area-function-to-acoustic level. This suggests a need for further research on this issue. If motor equivalence is manifested as the study suggests, it would only be one of many possible strategies.
Relevance to the Current Work: This study examines how two articulatory structures interact and contribute to the acoustic production of /u/. The current study examines how articulatory structures interact and change with the presence of a bite block in diphthong production.

Perkell, J. S. (2013). Five decades of research in speech motor control: What have we learned, and where should we go from here? *Journal of Speech, Language and Hearing Research, 56*(6), 1857-1874. doi:10.1044/1092-4388(2013/12-0382)

Objective: The author describes research in speech motor control over the last five decades, as observed from Ken Stevens' Speech Communication Group (SCG) in the Research Laboratory of Electronics at MIT.
Method: The article presents a limited overview of important discoveries and developments in the area of normal motor control of the vocal contract in the production of sound segments and syllables. The author examines acoustic analysis of articulatory movements. There are sections on methodological advances, scientific advances, and conclusions.
Results: Advancements in technology have led to the acquisition of more robust data sets, which reveal that variability in speech is universal. Improvements in brain imaging have allowed for more in-depth understanding of brain activity in healthy individuals while they are speaking. Research on coarticulation and reduction reveals that speakers can adjust their articulatory movements according to phonetic contexts. Speech kinematic studies have shown that articulatory movements in speech resemble other types of movement. Data have also revealed that the speech musculature is capable of producing forces much greater than is required for speech.
Conclusions: Research in speech motor control has seen significant advances in the past five decades. However, much research is still needed, especially in exploring the neural mechanisms that underlie normal and disordered speech production.
Relevance to the Current Work: This is an overview of research advancements in speech motor control, including kinematic and acoustic studies of articulatory movements. The current study explores kinematic and acoustic data of articulatory movements during production of diphthongs.

Smith, B. L. (1984). Effects of bite-block speech on intrinsic segment duration and fundamental frequency. *Journal of the Acoustical Society of America, 76*(1), *59*. doi: 10.1121/1.2021927

Objective: This study explores the theory that vowel and consonant durational differences

involve mechanical effects of the mandible.
Method: Six adults produced 72 stimuli, including six repetitions of all possible combinations of the vowels [i, u, æ, a], and the consonants [p,t,k]. All stimuli were produced with a bite-block held between the molars with clenched teeth.
Results: The presence of a bite-block affected the participants' speech but intrinsic durational and fundamental frequency differences remained the same.
Conclusions: Changes in the mechanics of speech do not seem to significantly affect vowel and consonant durational differences.
Relevance to the Current Work: This study examines how the presence of a bite block affects vowel and consonant production. The current study investigates how the presence of a bite block impacts diphthong production.

Tasko, S. M., & Greilick, K. (2010). Acoustic and articulatory features of diphthong production: A speech clarity study. *Journal of Speech, Language, and Hearing Research, 53*, 84-99. doi: 10.1044/1092-4388(2009/08-0124

Objective: The aim of this study was to investigate how clear speech affects acoustic and orofacial kinematic measures associated with diphthong production.
Method: Data were collected from 49 neurologically typical young adults. The speakers were instructed to say a sentence containing the target word, "combine," five times using clear speech. They then repeated a series of sentences containing the target word using conversational speech. Listener ratings were used to judge speech clarity and acoustic and articulatory kinematic analyses were performed on the diphthong /ɑɪ/ contained in the target word.
Results: Speaking clearly resulted in an increase in diphthong duration proportional to the rest of the word as well as larger F1 and F2 excursions and associated tongue and mandible movements. There was minimal evidence of change in formant transition rate.
Conclusions: Clear speech is accomplished through larger and longer, but not necessarily faster diphthong-related movements and transitions. These results are consistent with a simple model, which assumes that speech clarity is a result of reduced overlap of articulatory gestures.
Relevance to the Current Work: This study used acoustic and kinematic analysis to investigate diphthong production under two speaking conditions. The current study uses kinematic analysis to examine tongue and jaw movements during diphthong production under normal and perturbed speaking conditions.

Thibeault, M., Menard L., Baum, S.R., Richard, G., McFarland, D.H. (2011). Articulatory and acoustic adaptation to palatal perturbation. *Journal of the Acoustical Society of America. 129*, 2112-2120. doi: 10.1121/1.3557030

Objective: This study used electromagnetic articulography and acoustic recordings to estimate tongue configuration during production of the fricative /s/ and stops /t/ and /k/ in the presence of a palatal perturbation.
Method: Ten native speakers of English (six women, four men) between the ages of 18 and 35 and with no history of speech, language, or hearing impairment, participated in the study. Two artificial palates (thin and thick) were constructed from dental acrylic for each speaker. The artificial palates were fitted with ball clasps to hold them in place. After a 15-minute practice

period, the speakers produced ten repetitions of each of the target phonemes in seven different conditions.
Results: The kinematic and acoustic data analysis showed that fricatives were more affected by the perturbation than stops. While the thin and thick palates revealed similar acoustic effects overall, the thick palate lowered the center of gravity and the jaw was lower and the tongue moved further downward and backward than with the thin palate. Six of the speakers increased their acoustic center of gravity while three of the speakers decreased the center of gravity, resulting in a large standard of deviation for center of gravity measurements.
Conclusions: The large standard deviation for acoustic center of gravity measurements revealed that the speakers employed different strategies to adapt to the perturbation. The similar acoustic effects of the thin and thick palates may reveal that differences in articulatory movements may not have yielded salient acoustic changes, thus promoting the importance of including kinematic data in the study.
Relevance to the Current Work: This study used electromagnetic articulography and acoustic data to examine perturbation effects during speech. The current study also uses the same signal sources to examine perturbation effects on speech. The age of the sample used in the study is also similar to the age of the sample in the current study.

Westbury, J., Lindstrom, M., & McClean, M. (2002). Tongues and lips without jaws: A comparison of methods for decoupling speech movements. J*ournal of Speech Language and Hearing Research*, *45*, 651-662. doi: 10.1044/1092-4388(2002/052)

Objective: The study examined articulatory movement during speech in order to estimate the accuracy of certain methods for decoupling lip and tongue movements from the jaw. The methods for decoupling consisted of *translation-rotation* (TR) model, *only-translational* (OT) model, *only-rotational* (OR) model and *estimated-rotation* (ER) model.
Method: 44 typical young adult speakers of American English participated in the study. Markers were placed on the tongue, lips, and jaw to track the articulatory movements as the speakers read aloud the test sentence *She had your dark suit in greasy wash water all year.* The results from the OR, OT, and ER decoupling methods were then compared to the TR method ("Gold Standard").
Results: The positional errors, which were calculated relative to the TR decoupling method, were largest for the OT method and smallest for the ER method. Speed errors impacted the accuracy of the OT method during selected time samples.
Conclusions: Jaw movements during speech production are not clearly defined as simply translational or rotational. Decoupling articulatory landmarks is not a straightforward calculation in one or two dimensions. Sagittal plane movements of lower lip and tongue markers are decoupled from the jaw using multiple dimensions. Errors increase when rotation is not accounted for rather than translation. The ER method showed improvements in accuracy over any decoupling approach, which lead to increased understanding of the related movements between the tongue, lower lip, and jaw during speech.
Relevance to the Current Work: This study was valuable in decoupling the movements of the tongue and jaw in the current study.

APPENDIX B

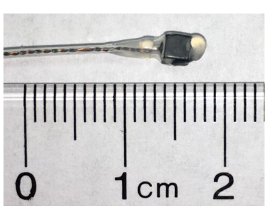
Informed Consent

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 people's speech movements change when the movement of the jaw is temporarily restricted. He will be assisted by Madison McHaley, Tanner Low, and Michelle Olson, who are graduate students in the department. You were invited to participate because you are a native speaker of Standard American English with no history of speech or hearing disorders**.**

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

- you will be seated in a sound booth in 106 TLRB, where you will read several sentences aloud as they are audio recorded
- then, using dental adhesive, the researchers will attach small (3 mm) sensor coils to your tongue, lower teeth, and lips to measure the movements of your articulators as you speak
- for the next 10 minutes you will talk with the researchers or read aloud from a magazine to help you get used to the sensors in and around your mouth; during this time, you will read aloud the target sentences several times
- a small bite block will be placed between your molars on both sides to prop your jaw open slightly; this will temporarily prevent it from moving, but you will still be able to speak, even if it feels unusual
- for the next 10 minutes you will read aloud the target sentences several times as the researchers record your speech
- the bite blocks will be removed, and during the next 6 minutes you will read the sentences again several times
- the tracking sensors will be removed, and you will read the sentences several times in the next few minutes
- your total time commitment will be no more than 60 minutes



tracking sensor bite block

Risks/Discomforts
There is a slight risk that you may feel discomfort as the tracking sensors are removed near the end of the study. This feels like peeling off a small Band-Aid. There may be a trace amount of glue residue on your tongue after the sensors come off, but this usually goes away of its own accord within a few minutes. To minimize your discomfort, the researchers will allow you to pull

away the sensors as slowly or as quickly as you like. The researchers will give you a piece of gauze to allow you to rub the tongue surface to aid in glue removal.

There is a slight risk that the bite blocks could fall backward in the mouth and trigger the gag reflex; they have a hole in the middle to tether them with dental floss.

Benefits

There are no direct benefits to you as a research subject. It is hoped, however, that the findings of this study will increase our understanding of the way speech movements are regulated, which in the future may help with the assessment and treatment of speech disorders.

Confidentiality

The research data will be kept in a locked laboratory on a password protected computer and only the researchers 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 primary 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:________

APPENDIX C

Stimulus Phrases

Stimuli- repeat 5 times every 2 minutes

I say ahree /əri/
I say ahrae /əræ/
I say ahroo /əru/
I say ahraw /ərɑ/

I’m an owl that hoots

The blue spot is on the black key again