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Articulatory Kinematic Differences During Adaptation to a Bite Block

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ABSTRACT

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The current study examined the effects of bite blocks on articulatory kinematics when producing /r/ within a phrase. Participants consisted of 20 young adults (10 males, 10 females) with no speech, language or hearing disorders. Participants produced the carrier phrase, *I say* __ with the nonsense words /əri/ (high front vowel), /əræ/ (low front vowel), /əru/ (high back vowel), /ərɑ/ (low back vowel). A Northern Digital Instruments Wave electromagnetic articulograph measured the articulatory movements while the speaker produced the stimuli in two conditions (Pre bite block and post bite block). Bilateral bite blocks were made using Express dental putty, which is a silicone impression material, in order to create an inter-incisal gap of 10 mm. The hull area (i.e., a boundary enclosing the total distance the sensor traveled during the target phrase) of the data for each sensor (i.e., tongue back, tongue mid, tongue front, lower lip, mandibular central incisor) was calculated for the individual nonsense words /eɪərɑ/, /eɪəræ/, /eɪəri/, and /eɪəru/. Results revealed kinematic differences across vowel phrases and between genders. The hull area of the tongue and jaw were significantly different for the vowel phrases /eɪəræ/, /eɪəri/, and /eɪəru/ compared to /eɪərɑ/. The hull area for the jaw for /eɪərɑ/ was significantly larger than the other vowel phrases. The between-gender analyses showed larger hull areas for males than females. Different motor equivalent strategies for tongue movements were observed when speakers produced /eɪərɑ/ and there were individual differences in compensating for the presence of the bite block.

Keywords: articulatory kinematics, motor equivalence, bite block, perturbation, adaptation

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DESCRIPTION OF THESIS STRUCTURE

This thesis, Articulatory Kinematic Differences During Adaptation to a Bite Block, 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 annotated bibliography is found in Appendix A, the research consent form information is found in Appendix B and the stimulus phrases in Appendix C.

Introduction

The way in which individuals produce speech is intricate and multifaceted. Evidence in the literature suggests that muscle activity across the components of the speech production mechanism is highly coordinated. Theories regarding coordination of the articulators include the notion of *motor equivalence*, which reflects the fact that similar perceptual and acoustic outputs can result from many different combinations of articulator movements. (Brunner et al., 2011; Brunner & Hoole, 2012; Hughes & Abbs, 1976; McFarland & Baum, 1995; Perkell, Matthies, Svirsky, & Jordan, 1993)

Motor Equivalence

There are multiple motor areas of the brain that control the movements of our bodies. These motor areas send signals to the muscles of each articulator (e.g., tongue, lips, jaw). The relative contribution of each articulator may vary during speech, and different articulatory configurations can be used to achieve the same result. In the context of speech motor control, the term motor equivalence is used when different articulatory strategies are implemented to produce a similar acoustic output. By using several articulators in different ways the vocal tract shape changes, but the end result is a similar acoustic output (Brunner & Hoole, 2012). The relative contributions of the jaw, upper and lower lip coordination, tongue placement and velopharyngeal constriction can vary during speech.

Concerning the use of jaw muscles, Gentil (1992) found that speakers used as few as three or as many as six of the seven mandibular elevator groups during speech production. The muscles selected for jaw closure in the experimental utterances varied greatly depending on the speech stimuli and the rate of the utterance. Differences in mandible movements may be linked to the size and shape of each participant's mandible. Even though different jaw muscles were used, the speech goal was always achieved.

Differences in upper and lower lip movements have been observed during speech production. An individual may increase the activation of the levator or depressor muscles that attach to the lip when producing a bilabial sound (e.g., /b/). However, when producing sounds that require less lip movement (i.e., /s/, /t/, /k/), there is a decrease in the activation of the lip. In 1976, Hughes and Abbs recorded vertical displacements of the lower lip, upper lip and jaw during a nonsense word repetition task. The results of this study showed differences in the contribution of each articulator to bilabial closure. Variations were evident in the amount of upper lip movement that contributed to complete oral closure. Hughes and Abbs stated that "large upper lip displacements were evident particularly when either the jaw or the lower lip (or both) did not achieve their normally large displacements (i.e., it appears that the upper lip takes over and compensates for the decreased contributions of the jaw and lower lip)" (p. 210).

Hughes and Abbs (1976) found that some individuals used the upper lip to compensate for the decreased displacement of the lower lip and jaw in order to achieve complete oral closure. The lower lip movements were slightly smaller than the movements made by the jaw during the production of the vowel /i/. Even though the lower lip and jaw displacements varied between the participants, each participant showed displacement patterns where the lower lip and jaw movements were highly sensitive to each other. The degree of motor equivalence found among participants depended on the specific phonemes being produced, the rate at which speech was produced, and the size and shape of the articulators. For a given bilabial closure, the relative contributions of the upper lip, lower lip, and jaw movements can vary within and across speakers. The closure still occurs, but there are different combinations of upper lip, lower lip and jaw movements that lead to the closure (Hughes & Abbs, 1976).

A trading relationship, when one articulator moves more as another moves less, has been reported between the position of the tongue and the protrusion of the lips when producing /u/ and /ʃ/. Perkell et al. (1993) observed this phenomenon in individuals while producing /u/. To produce this vowel, the lips are rounded and the tongue body is moved to a high back position against the velum and the palate to form a constriction. Greater lip rounding was associated with less tongue raising and vice versa. Coordination of the tongue and lips varied when producing /u/, but all participants produced normal acoustic results.

Brunner and Hoole (2012) found a trading relationship between the position of the tongue and the amount of protrusion of the lips in 3/6 of the participants who produced the phoneme /ʃ/ in the word /ʃaxa/. The more a speaker retracted the tongue, the less the lips were protruded; a less retracted tongue was associated with more lip protrusion. Each position of the tongue and lips resulted in a similar acoustic output. The other three participants produced acoustic output that varied slightly depending on the tongue placement. The variation of the tongue placement was kept within the appropriate range needed for the listener to recognize the sound. As these articulatory differences approach the limit of perceptual acceptance, the speaker must coordinate the articulators in order for the acoustic quality to be preserved. Otherwise, a listener may perceive these changes as a different phoneme altogether which may result in unintelligible speech and/or communication breakdowns.

Motor equivalence allows a speaker flexibility in producing sounds which may be valuable in several situations. For example, neurological damage may disrupt the typical activation of articulatory muscles resulting in the inability to produce phonemes as the speaker did premorbidly. In order to communicate effectively following a neurological event which impairs speech production, the individual may need to change articulatory movements to accomplish intelligible speech because previously successful articulatory strategies may no longer work (Brunner & Hoole, 2012).

Dental devices can cause a change in speech production strategies in order to produce speech that sounds normal. Dental devices may lead a speaker to use different strategies (e.g., tongue placement, jaw movement) in order to achieve speech that is acoustically similar to the speech produced before insertion of the appliance. Each one of these potential causes of change in speech production may lead a speaker to use motor equivalent strategies. The current study will examine the use of motor equivalence in typical adults.

Perturbation

A perturbation causes a deviation in the operation of a system. A perturbation can be caused by a device or object placed in the oral cavity that impairs the movement of the articulators, and this may affect speech production. Introducing a perturbation into the oral cavity temporarily changes the ability of the articulators to function typically. Such perturbations can occur in instances that are commonplace (e.g., an orthodontic retainer). There are two main types of perturbation: static and dynamic.

Static perturbation occurs when the size and shape of the device placed in the oral cavity is consistent and present for all utterances. This type of perturbation is most commonly used in research as it requires minimal equipment and thus is more readily available. Research on static perturbation has included the use of bite blocks, which are small devices placed between the molars. This causes jaw stabilization during research experiments (McFarland & Baum, 1995). When natural jaw movements are prevented, increased tongue movements can compensate for the missing contributions of the jaw. The speaker still produces almost typical speech by creating constriction sizes that are similar to those formed in unperturbed speech (Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). In perturbed speech, motor equivalent strategies are often used because the speakers are blocked from using their usual strategies (Brunner & Hoole, 2012). Speakers must coordinate the articulators in atypical ways when their speech is perturbed. For example, if an individual's jaw is stabilized by the presence of a bite block, the tongue and the lips must compensate in order to produce acceptable and intelligible speech.

Dynamic perturbation is when ongoing speech movements are modified by a device (e.g., robotic arm) which causes an atypical disturbance to articulation. This type of perturbation would not occur in natural speech, but only in laboratory experiments. Kelso et al. (1984) performed complex dynamic perturbation experiments which showed the coordination of individual articulators. Coordinative structures theory suggests that there are functional synergies whereby a group of articulators function as a unit to achieve an outcome (e.g., the upper lip, lower lip, and jaw work together to achieve bilabial closure). As a result, the cortex does not micromanage each movement, but instead the lower levels of neural control are delegated to achieve the articulatory goal. In this 1984 study, observations made during articulatory movements showed that muscles and joints responded quickly and precisely to the dynamic perturbation during speech production. This led to the understanding that articulatory structures work together in functional groupings to produce speech.

Articulatory muscles and structures are grouped together in order to accomplish a specific task (e.g., the jaw may be grouped with the lower lip to produce /b/, while the jaw may be grouped with the tongue to produce /t/.) Kelso et al. (1984) observed the effects of a robot arm randomly disrupting speech by restricting the jaw elevation during bilabial closing movements.

As a result of this dynamic perturbation, the lips compensated by increasing their movements. The upper lip demonstrated increased inferior movements during final /b/ closure when the jaw was perturbed (i.e., robot arm pulling down on the jaw) as compared to unperturbed (i.e., typical speech) trials immediately after the perturbation stopped. When one articulator was disrupted during speech production, then another articulator compensated in order to produce the intended sound.

Compensatory strategies that speakers use show substantial individual variability when a perturbation (e.g., a retainer) is present. Studies have examined the effects of an array of devices (e.g., retainers, palatal expanders) on speech sound production (Kulak Kayikci, Akan, Ciger, & Ozkan, 2012; Paley, Cisneros, Nicolay, & LeBlanc, 2016; Stevens, Bressmann, Gong, & Tompson, 2011). The retainers affected the production of vowels as well as consonants. Kulak Kayikci et al. (2012) found no significant changes when the participants wore the Hawley retainer when producing /ɑ/, /e/ and /u/. Changes were observed in the production of /s/, /z/ and /i/. Consonants require greater precision than vowels which would make the impact of the perturbation more obvious for the consonants. Some individuals adapted to the presence of the perturbation more quickly than others (i.e., adaptation period lasted anywhere from one week to three months), but /s/, /z/ and /i/ required more time to adapt to the perturbation. Overall, the observed effects may be due to the change in tongue posture and palatal volume while wearing the retainer.

Paley et al. (2016) observed the effects of a fixed labial orthodontic appliance on speech production in twenty-three individuals. Sixteen of the participants presented with Angle Class I malocclusion, five presented with Class II Division 1 malocclusion, and two presented with Class III malocclusion. The specific target sounds examined were: /t/, /p/, /f/, /s/, /ʃ/, /t͡ʃ/, /d͡ʒ/,

/k/, /θ/, /l/ and /m/. The findings showed that the appliances affected the production of sibilant and stop sounds, and that speakers showed personal differences when adapting to a perturbation. The ability to adapt speech to the presence of the appliance, both immediately and over time, depended on the severity of malocclusion before the placement of the appliance. Brunner and Hoole (2012) examined the effects of perturbation on speech production using two different types of palatal prosthesis (i.e., central palate and an alveolar palate). The central palate lowered and flattened the palatal arch while the alveolar palate moved the alveolar ridge posteriorly. Results from this study showed that 2/6 participants used no motor equivalence when the alveolar palate was placed as measured by the correlation between articulatory and acoustic parameters; 1/6 demonstrated perfect motor equivalence with no correlation between acoustic and articulatory parameters and a positive correlation between lip and tongue contributions; 3/6 participants showed more variability in tongue position than lip position. The findings showed that the use of motor equivalence increased for those with a central palate compared to those with an alveolar palate.

Bite blocks create a fixed jaw position which can cause speech distortions. McFarland and Baum (1995) compared jaw-free or normal speech production to perturbed speech by using a large bite block (22.5 mm for vowels and 10 mm for consonant vowel [CV] stimuli) and a small bite block (2.5 mm for vowels and 5 mm for CV stimuli) placed at the incisors. The participants produced three vowels (i.e., /i/, /ɑ/, /u/), three consonants (i.e., /p/, /t/, /k/) and the voiceless fricatives in isolation ten times each. The large bite block caused more disruptions in speech production than the small bite block, even for the vowel /ɑ/ which is produced with a large jaw opening. The bite blocks did not significantly affect the duration of vowels or stop consonants, but significantly influenced the vowel formants. The formant frequency F1 was significantly higher when perturbed by a large bite block and the formant frequency F2 was only significantly higher for the vowel /u/ when perturbed by a large bite block. These changes in speech production showed the effects of a bite block when producing certain vowels and consonants.

The effects of perturbation vary among individuals, as well as with the type of perturbation and the specific speech sounds which are produced. A dynamic perturbation requires quick and precise changes to articulatory placement in order to produce speech, while a static perturbation may require a certain amount of time in order to adapt to the presence of a novel structure. The current study involved the use of a static perturbation (i.e., bite blocks) while producing /r/ in different contexts.

Adaptation

The process of adjusting to new conditions is referred to as *adaptation*. 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” (pg. 1866). The need for speech adaptation arises when the speech mechanism cannot achieve adequate speech goals. Research studies using perturbation have examined how speakers adapt to the introduction of a perturbation.

The findings of McFarland and Baum (1995) revealed that compensating for an increased jaw opening was not complete or immediate. More time was needed for consonants than for vowels to adapt to the perturbation and the amount of time needed to adapt was highly variable. Some speakers adapted rather quickly to any changes in their oral structure, while others never fully adapted (Flege, Fletcher, & Homiedan, 1988).

The process of adaptation varies with the speech stimuli, the type of perturbation, and the amount of time the articulators are perturbed. Stevens et al. (2011) observed perceptual differences in their subjects' speech while adapting to the presence of a rapid palatal expander. The perceptual ratings from listeners showed that over a period of time while wearing the rapid palatal expander, speech acceptability increased, but the perceptual acceptance was still lower than before the expander was placed. Once the expander was removed completely, the speech acceptability returned to pre-expander levels.

Consonants, which require greater articulatory precision than vowels, show greater speech production consistency (Flege et al., 1988). McFarland and Baum (1995) found that speech adaptation is quicker and more complete for vowels than for consonants. However, individuals who presented with childhood articulation disorders took longer to adapt to the perturbation especially if the perturbation was near or around the alveolar ridge. Speakers greatly differed in articulatory skill and adaptation abilities (McFarland & Baum, 1995; Stevens et al., 2011).

American English /r/

The phoneme /r/ is complex and kinematically variable. It is well known that /r/ can be produced using different tongue configurations (i.e., bunched or retroflexed), but those different configurations do not change the sound a listener hears. Studies have shown that there are different ways to produce /r/ without compromising the listener's ability to understand the message (Guenther et al., 1999; Nieto-Castanon et al., 2005; Westbury, Hashi, & Lindstom, 1998).

For most speakers, /r/ is produced with either a bunched or a retroflexed tongue shape. A bunched tongue shape includes a lowered tongue tip and a raised tongue dorsum while a retroflexed tongue shape includes a raised tongue tip and a lowered tongue dorsum. Neither placement is better or more precise than the other, but they reflect individual differences in speech production. Different tongue shapes may be used to produce /r/, depending on the phonetic context. An individual may use a bunched tongue shape when producing /r/ in isolation, but may use a mixture of a bunched tongue and a retroflexed tongue shape when producing connected speech (Nieto-Castanon et al., 2005).

Differences in vocal tract shape for /r/ do not necessarily change the acoustic output. Westbury et al. (1998) found that when producing /r/, speakers used a bunched tongue shape while others were noticeably retroflexed. However, some participants produced tongue shapes that were not matched to either of these descriptive labels. Most of those who did not produce either a retroflexed or a bunched tongue shape produced /r/ with the tongue shifted down and to the left. The differences in tongue shape among the participants were not associated with differences in formant frequencies. The generally accepted classes of tongue shapes for /r/ (e.g., retroflexed or bunched) may often be more assumed than real. Many of the participants only inconsistently used these configurations when producing /r/ and no two participants created identical tongue shapes. The tongue shapes for /r/ changed depending on the phonetic context. Similar shape and movement of the tongue appeared when /r/ was produced in the initial position followed by a back vowel. Formations of different tongue shapes and movements appeared in /r/ clusters (e.g., in the word *street*). The phoneme /r/ can be produced with a relatively large variation in the vocal tract shape without changing the sound.

The articulatory makeup for /r/ includes different combinations of two constrictions of the vocal tract. Guenther at al. (1999) found a trading relationship between the tongue back height and the front horizontal position of the tongue. They stated that "the primary acoustic cue for /r/ is relatively simple and stable: a deep dip in the trajectory of the third spectral energy peak of the acoustic waveform, or third formant frequency" (p. 2854). The identifying marker for /r/

consists of a lower third formant on the spectrogram. Narrowing of the vocal tract leads to this reduction of the formant F3. Nieto-Castanon et al. (2005) stated that “the production of American English /r/ in different phonetic contexts shows a functional relationship between acoustic stability and articulatory variability” (p. 3210). This relationship shows the amount of articulatory variability that occurs in order to produce the slight change in the formant frequency F3. The change in the formant frequency F3 must take place in order for /r/ to be identified.

The formant frequencies of F3, F4 and F5 are reported to be associated with the length of the posterior oral cavity. Zhou et al. (2008) examined the differences between F4 and F5 when two participants produced /r/. Both participants had similar palate lengths, palate volumes, vocal tract lengths, and overall stature. Data gathered from MRI scans of the vocal tract showed that each participant produced characteristic F4/F5 patterns. The distance between F4 and F5 was larger for the retroflexed /r/ than the bunched /r/. The results of this study suggested that F4 and F5 spacing were reliable indicators of tongue shape, at least for either a retroflexed or a bunched tongue shape.

Tiede, Boyce, and Epsy-Wilson (2007) explored the different articulatory strategies an individual uses when producing /r/ during perturbation (i.e., from a palatal prosthesis). Each participant produced /ɑrɑ/, /iri/, and /uru/ in isolation 10 times per condition (i.e., preperturbation, immediately following prosthesis insertion, post adaptation-prosthesis still in place, immediately following prosthesis removal). All participants showed distinct preperturbation postural preferences and produced both bunched and retroflexed production postures. In response to the perturbation, decreased tongue tip angle was observed. Because the same sized palatal prosthesis was used for each participant (i.e., male and female), the perturbation affected the larger male vocal tract less than the female. The production of /r/

consisted of more than one strategy and each strategy produced a specific formant structure. On the basis of their findings, these authors suggested that the tongue posture for /r/ at the motor planning level can be determined by the coarticulation constraints, perturbation, and individual decision of the easiest way to produce /r/.

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 and how their responses may provide evidence of motor equivalent strategies that differ across individuals. It was hypothesized that there would be articulatory kinematic differences across vowels for all participants, as well as for each vowel before the bite block was inserted. It was also hypothesized that differences in articulator size would result in between-gender differences for the hull areas (i.e., a boundary enclosing the total distance the sensor traveled during the target phrase). As a result of the variations across vowels and differences in articulator sizes, motor equivalent strategies will be seen across participants.

Methods

Participants

Twenty individuals consisting of ten males and ten females ages 22-28 with no history of speech, language, or hearing disorders participated in the study. They were recruited by word of mouth, and each signed a consent form which had been approved by the Brigham Young University Institutional Review Board. Participants received $10 in compensation for their time.

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 incisor 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. 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 Express STD putty, which is a silicone impression material. A small zip tie was used to hold the putty in place while it hardened and to assist 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 was custom adjusted 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 speech targets were produced as part of a carrier phrase, *I say* ______. Stimuli included the nonsense words /əri/ (high front vowel), /əræ/ (low front vowel), /əru/ (high back vowel), /ərɑ/ (low back vowel). The experimenter modeled the task, and the participant was instructed to say each stimulus phrase once with a breath in between phrases. The list, which was randomized for target sequence for each speaker, was repeated five times.

Procedure

Each participant produced the speech stimuli prior to the sensors being glued to the articulators to allow acoustic recordings of typical speech. Then the dB calibration recording was made with the participant saying /ɑ/ for 5 seconds. After the sensors were attached, and at 2-minute intervals during the following 6 minutes, additional recordings were made to track the process of adaptation to the presence of the sensors. Between the recordings the participants engaged in continuous talking/reading aloud to help them adapt to the presence of the sensors. At the 6-minute mark, the participants produced the speech stimuli once again in order to gather pre bite block data. Immediately after the bite block was inserted the participants produced the speech stimuli at 2-minute intervals during the next 6 minutes with the bite block still in place while the data were recorded. Immediately after the bite block was removed, the participants produced the speech stimuli in order 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-BB) and immediately after the bite block was inserted (Post-BB).

Kinematic Analysis

A custom Matlab application was created to segment the longer recordings into individual target phrases which were saved as separate files (i.e., "I say /əri/," "I say /əræ/," "I say /əru/," "I say /ərɑ/"). An additional custom Matlab application was created to segment the recording directly following the fricative /s/ and ending after the final vowel (e.g., /i/, /u/, /æ/, /ɑ/) in order to extract the dependent measures (see Figure 1). When segmenting the acoustic and kinematic stimulus phrases in order to analyze /r/, the acoustic waveform had no distinct separation from the diphthong /e͜ɪ/ in *say* to the /ə/. In addition, no distinction could be made from the /ə/ to the /r/ or from the /r/ to one of the four corner vowels (i.e., /ɑ, æ, i, u/). As a result, the total area that each sensor traveled was calculated for the individual nonsense words /e͜ɪərɑ/, /e͜ɪəræ/, /e͜ɪəri/, and /e͜ɪəru/. The challenges associated with reliably segmenting the /r/ from the surrounding phonemes led to the decision to analyze each word as a whole, rather than attempting to identify specific articulatory gestures.

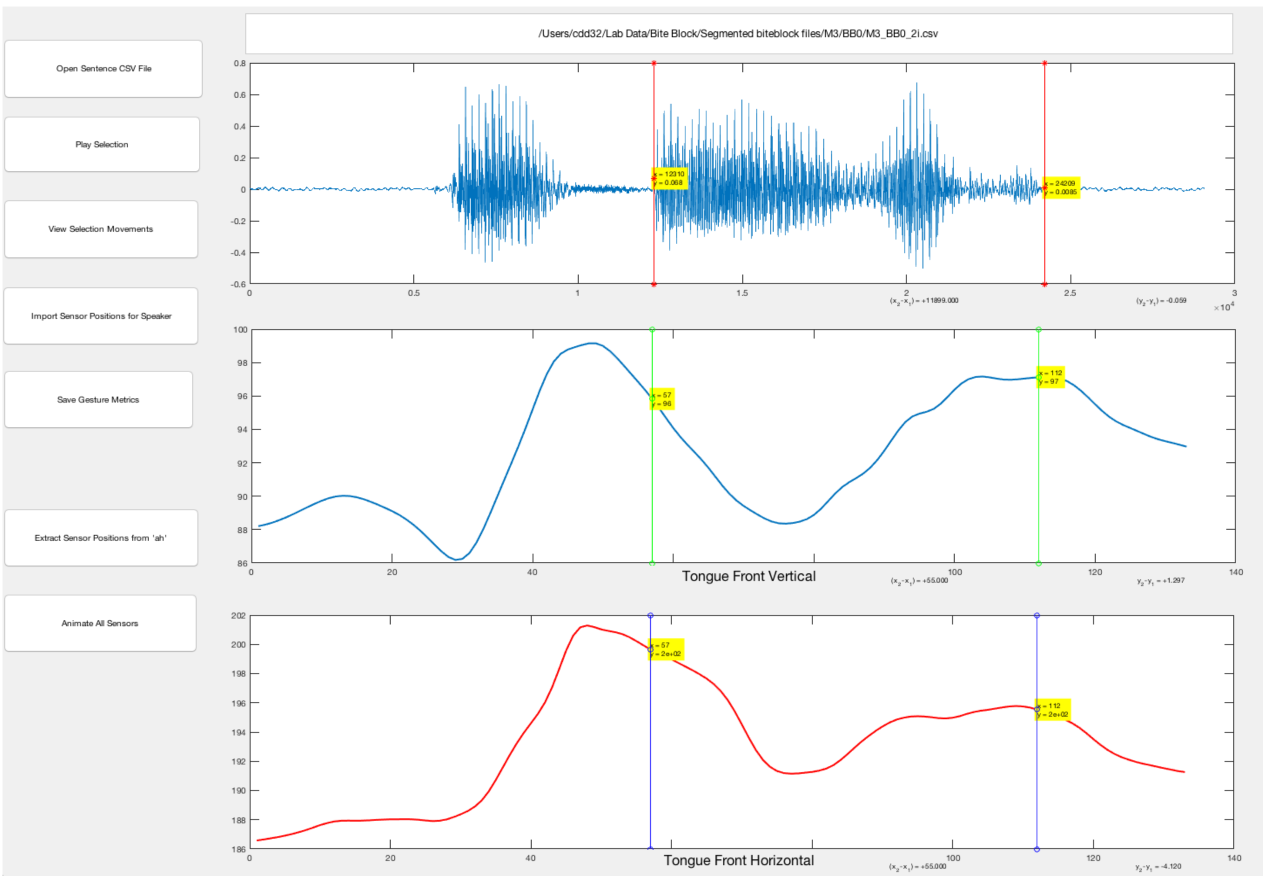

Figure 1. Segmentation of stimuli directly following the fricative and ending after the final vowel. Panel 1 - acoustic waveform of the stimulus phrase. Panel 2 - tongue front movements in the horizontal plane (mm). Panel 3 - tongue front movements in the vertical plane (mm).

This application extracted measures of the tongue and jaw displacements (see Figure 2) by measuring the hull area (i.e., the total area the sensor traveled during the stimulus phrase) of the sensor movement in mm² (Sensor). The hull area of the jaw movement (i.e., the total area the jaw traveled at the location directly closest to each sensor during the stimulus phrase) was measured in mm^2 (Jaw). The ratio between the sensor movement and jaw movement (Ratio) was calculated for each repetition of the stimuli. The relative contributions of the jaw and tongue were computed by decoupling their movements.

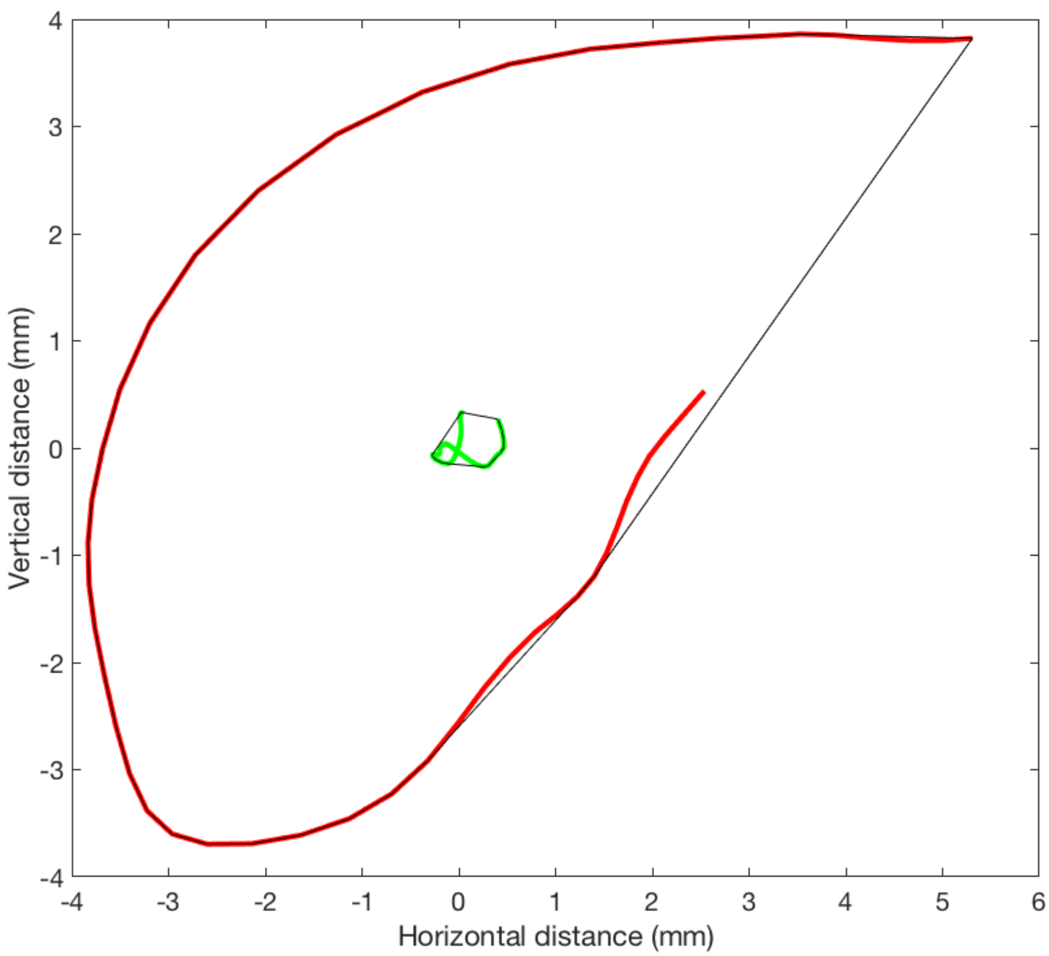

Figure 2. The hull area of the tongue mid and jaw movements for a male producing /i/. The red line represents the tongue mid movements with the black line around it creating the hull area in mm^2. The green line represents the jaw movements with the black line around it creating the hull area in mm^2.

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 et al., 1998) 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 back, mid and front tongue sensor positions from the kinematic recording of the sustained /ɑ/ 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 back, middle, and front tongue sensors 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.

Statistical Analysis

The hull area means for the five utterance repetitions for each measure (i.e., Sensor, Jaw and Ratio) for each vowel were calculated in Excel for statistical analysis with SPSS (version 25). A repeated measures analysis of variance was used with vowel (i.e., /ɑ/, /æ/, /i/, /u/) as the within-subjects factor and speaker gender as a between-subjects factor. Concurrent contrasts were performed to test for significant differences between /ɑ/ and the other three vowels. A second repeated measures analysis of variance was used to test for significant differences in Sensor movements from Pre-BB to Post-BB for each vowel phrase. When the Mauchly test revealed violations of the sphericity assumption of the repeated measures ANOVA, the Huynh-Feldt adjusted (non integer) degrees of freedom were used. A one-way ANOVA was also to test for difference between genders in each dependent variable for all vowels. Both sets of ANOVA tests were run separately for both the Pre-BB and Post-BB conditions.

Results

A Repeated Measures ANOVA calculated the main effect for the differences across vowels for Sensor movement, Jaw movement and Ratio between sensor and jaw movements (see Tables 1). Sensor movement, Jaw movement and the Ratio between sensor and jaw movements across vowels compared to /ɑ/ (see Tables 2, 6, 10). The means and standard deviations were calculated for each hull area metric (i.e., Sensor, Jaw, and Ratio) for the Pre-BB and Post-BB conditions (see Tables 4, 5, 8, 9, 12 and 13; see Figures 3-8). The data from the female participants F5, F9 and the male participant M5 were removed from statistical analysis due to tracking errors during data collection. Because of the number of tests conducted, the significance level used throughout analysis was $p < .01$.

Pre-BB Sensor

The repeated measures ANOVA main effect for Sensor movements showed significant differences in the Pre-BB condition for the following: TB, TM, TF and LL hull area across vowels (see Table 1); /æ/ had smaller movements than /ɑ/ for TB (see Table 2); /i/ had smaller movements than /ɑ/ for TB, TM and TF (see Table 2); /u/ had smaller movements than /ɑ/ for TB, TM and TF (Table 2). The one-way ANOVA showed no significant differences at $p < .01$ for Sensor movements between genders for each vowel (see Table 3), although the trends were for larger hull areas for men than women.

Post-BB Sensor

The Sensor movements in the Post-BB condition showed significant differences for the following: the hull area for TB, TM and TF across vowels (see Table 1); /æ/ had smaller movements than /ɑ/ for TB and TM (see Table 2); /i/ had smaller movements for /ɑ/ for TB, TM and TF (see Table 2); /u/ had smaller movements for /ɑ/ for TB, TM, and TF (see Table 2). The one-way ANOVA at $p < .01$ showed no significant differences for Sensor movements between genders for each vowel (see Table 3), although the trends were larger for larger hull areas for male (M) than female (F).

Pre-BB Jaw

The repeated measures ANOVA main effect for Jaw movements showed significant differences in the Pre-BB condition for the following: TB, TM, TF and LL hull areas across vowels (see Table 1); /i/ had smaller movements than /ɑ/ for each articulator (see Table 6); /u/ had smaller movements than /ɑ/ for each articulator (Table 6). The one-way ANOVA showed no significant differences for Jaw movements between genders for each vowel (see Table 7).

Post-BB Jaw

No significant differences were found in the Post-BB condition for the repeated measures ANOVA as a main effect (see Table 1 and Table 6) and the one-way ANOVA (see Table 7) for Jaw movements.

Pre-BB Ratio

The repeated measures ANOVA main effect for the Ratio showed significant differences in the Pre-BB condition for the following: TB, TM, TF and LL hull areas across vowels (see Table 1); /æ/ had smaller movements than /ɑ/ for TB and TM (see Table 10). The one-way ANOVA showed significant differences for /ɑ/ for TB, /æ/ for TB, TM, TF and /i/ for TB.

Post-BB Ratio

The Ratio in the Post-BB condition showed significant differences for the repeated measures ANOVA for the following: TB hull area across vowels (see Table 1); /u/ when compared to /ɑ/ for TB and TM (see Table 10). The one-way ANOVA showed significant differences between genders for /i/ for TB (see Table 11).

The repeated measure ANOVA between-subjects effects reflected gender differences when vowels were grouped together. Significant differences were found for Ratio for TB, $F(1, 15) = 34.510$, $p = <0.001$, ES .697; Ratio for TM, $F(1, 15) = 10.045$ $p = 0.006$, ES .401; and Ratio for TF, $F(1, 15) = 9.070$, $p = 0.009$, ES .377 in the Pre-BB condition. No significant differences were found for Sensor or Jaw in either condition.

Significant gender interactions were found for the Pre-BB condition for TM sensor $F(3, 45) = 2.938$, $p = 0.043$, ES .164. Pre-BB condition for TM Sensor also showed a vowel contrast which indicated that males had a larger /u/ when compared to /ɑ/ than females $F(1, 15) = 7.312$, $p = 0.016$, ES .328. For the Pre-BB condition, the TB Ratio showed a significant interaction of vowel with gender $F(1.774, 26.613) = 6.019$, $p = 0.009$, ES . 286. Males had a larger /i/ when compared to /ɑ/ difference than females $F(1, 15) = 5.927$, $p = 0.028$, ES .283.

The repeated measures ANOVA that tested for significant within-subjects differences in Sensor movements from the Pre-BB to Post-BB condition for each vowel revealed significant decreases in movement for /æ/, but not the other vowels at the $p < .01$ level, although there was a trend for similar decreases for /ɑ/. The /æ/ phrase sensor movements for TM and TF were significantly different from Pre-BB to Post-BB with a trend for reduced movements in TB (see Table 14).

Table 1

Repeated Measures ANOVA Main Effect Differences Across Vowels for Sensor Movement, Jaw Movement and the Ratio Between Sensor and Jaw Movements

	Sensor				Jaw				Ratio			
	df	*F*	*p*	ηp2	df	*F*	*p*	ηp2	df	*F*	*p*	ηp2
Pre-BB												
TB	3.000	29.429	<0.001	0.662	3.000	23.804	<0.001	0.613	3.000	23.804	<0.001	0.613
TM	3.000	39.027	<0.001	0.722	3.000	23.827	<0.001	0.614	3.000	23.827	<0.001	0.614
TF	2.527	30.205	<0.001	0.668	3.000	23.473	<0.001	0.610	3.000	23.473	<0.001	0.610
LL	2.289	10.750	<0.001	0.417	3.000	22.807	<0.001	0.603	3.000	22.807	<0.001	0.059
Post-BB												
TB	3.000	7.322	<0.001	0.328	1.620	0.946	0.384	0.059	2.592	4.567	0.010	0.233
TM	3.000	13.132	<0.001	0.467	1.661	0.800	0.439	0.051	3.000	3.218	0.031	0.177
TF	2.419	9.980	<0.001	0.400	1.638	0.816	0.432	0.052	3.000	3.511	0.023	0.190
LL	2.243	4.559	0.015	0.233	1.638	0.819	0.431	0.052	1.735	1.078	0.347	0.067

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 2

Sensor Movement Concurrent Contrast Differences Between Vowels When Compared to /a/

		/æ/		/i/		/u/	
		F	*p*	*F*	*p*	*F*	*p*
Pre-BB							
	TB	11.361	0.004	28.197	<0.001	67.575	<0.001
	TM	7.621	0.150	35.688	<0.001	72.769	<0.001
	TF	1.825	0.197	27.626	<0.001	26.506	<0.001
	LL	4.209	0.058	3.600	0.077	6.151	0.025
Post-BB							
	TB	9.171	0.008	9.709	0.007	15.725	<0.001
	TM	15.673	0.001	22.300	<0.001	37.542	<0.001
	TF	6.113	0.026	13.379	0.002	22.813	<0.001
	LL	0.463	0.507	5.914	0.028	4.892	0.043

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 3

One-Way ANOVA - Sensor Movement Differences Between Gender for Each Vowel

		/ɑ/			/æ/			/i/			/u/		
		df	*F*	*p*	df	*F*	*p*	df	*F*	*p*	df	*F*	*p*
Pre-BB													
	TB	1	7.913	0.013	1	5.082	0.040	1	6.926	0.019	1	6.629	0.021
	TM	1	7.887	0.013	1	5.828	0.029	1	6.753	0.020	1	5.346	0.035
	TF	1	5.578	0.032	1	3.467	0.082	1	6.236	0.025	1	5.456	0.034
	LL	2	0.423	0.525	1	0.218	0.647	1	0.105	0.750	1	0.368	0.553
Post-BB													
	TB	1	5.916	0.028	1	5.340	0.035	1	6.195	0.025	1	5.675	0.031
	TM	1	6.151	0.025	1	3.537	0.080	1	6.599	0.021	1	4.467	0.052
	TF	1	1.602	0.429	1	1.656	0.218	1	2.002	0.178	1	1.417	0.252
	LL	1	0.235	0.635	1	0.846	0.372	1	1.037	0.325	1	0.158	0.696

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 4

Hull Area of the Movement of Sensors in mm² for Pre-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	87.8	45.4	75.3	32.1	43.3	24.1	40.2	15.9
	TM	87.9	36.6	78.5	32.7	43.4	22.4	44.5	15.1
	TF	101.2	39.2	102.0	39.2	52.2	25.1	52.4	17.5
	LL	50.3	47.7	63.9	60.2	42.2	61.6	40.7	53.2
Male									
	TB	152.5	49.0	119.6	46.6	101.3	57.8	74.4	34.4
	TM	158.8	62.5	129.4	51.0	92.3	48.6	75.3	34.7
	TF	170.3	73.9	149.0	61.0	114.3	66.0	102.7	58.5
	LL	67.5	59.8	78.6	68.3	52.2	65.4	57.2	58.1

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

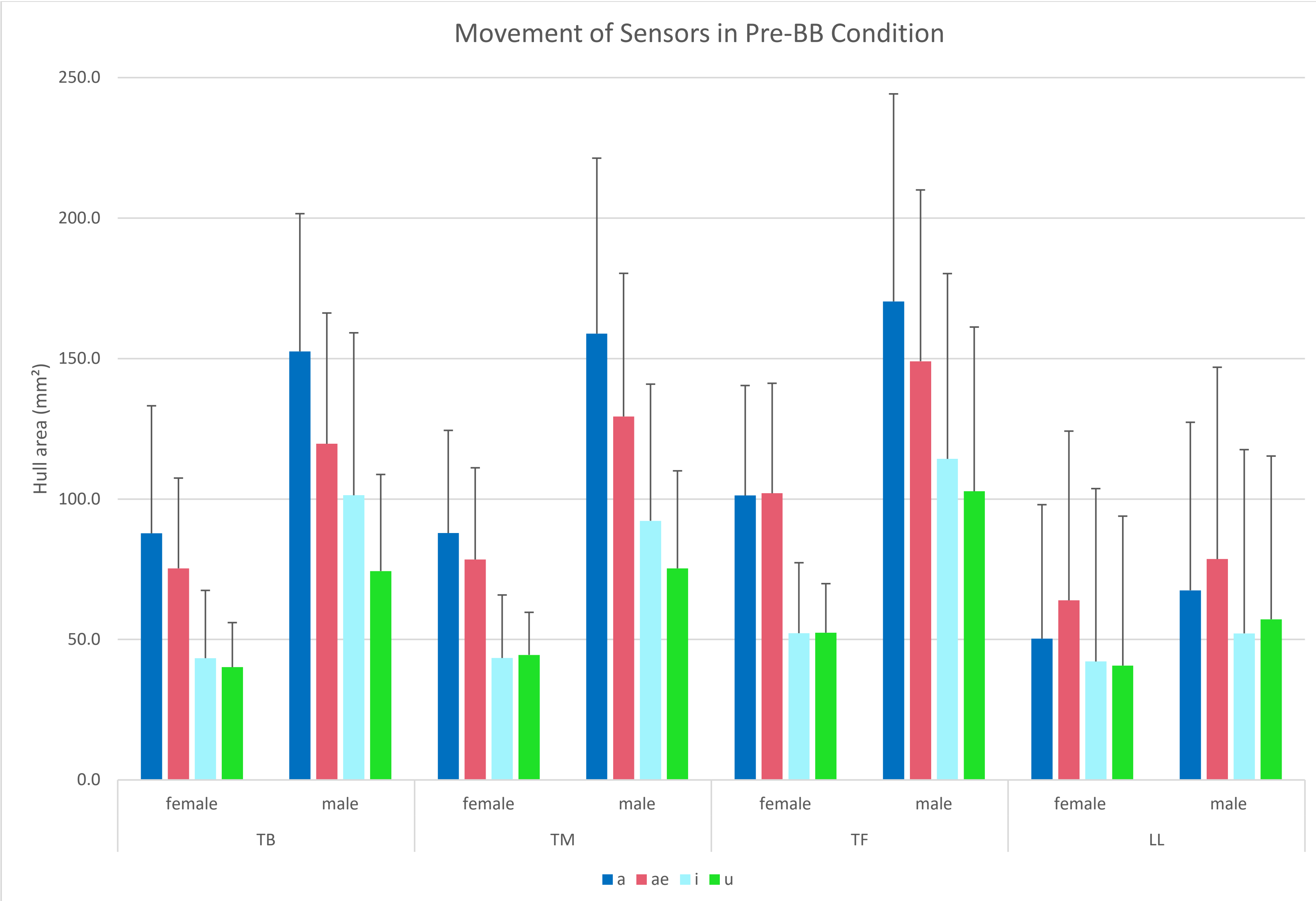

Figure 3. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 5

Hull Area of the Movement of Sensors in mm² for Post-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	67.3	47.1	48.8	25.7	38.0	28.6	39.8	30.5
	TM	75.4	47.4	57.8	42.0	37.4	20.2	45.5	31.1
	TF	102.2	62.7	77.7	48.3	61.4	40.4	65.1	42.1
	LL	46.6	42.2	52.4	48.8	41.6	42.8	29.0	22.8
Male									
	TB	129.8	57.5	97.5	54.3	92.4	55.5	86.2	46.9
	TM	135.7	52.2	99.6	48.8	89.8	54.4	83.4	41.2
	TF	142.2	67.1	117.6	74.7	103.9	75.9	95.6	60.5
	LL	37.8	32.3	35.9	22.0	25.4	20.7	33.5	23.9

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

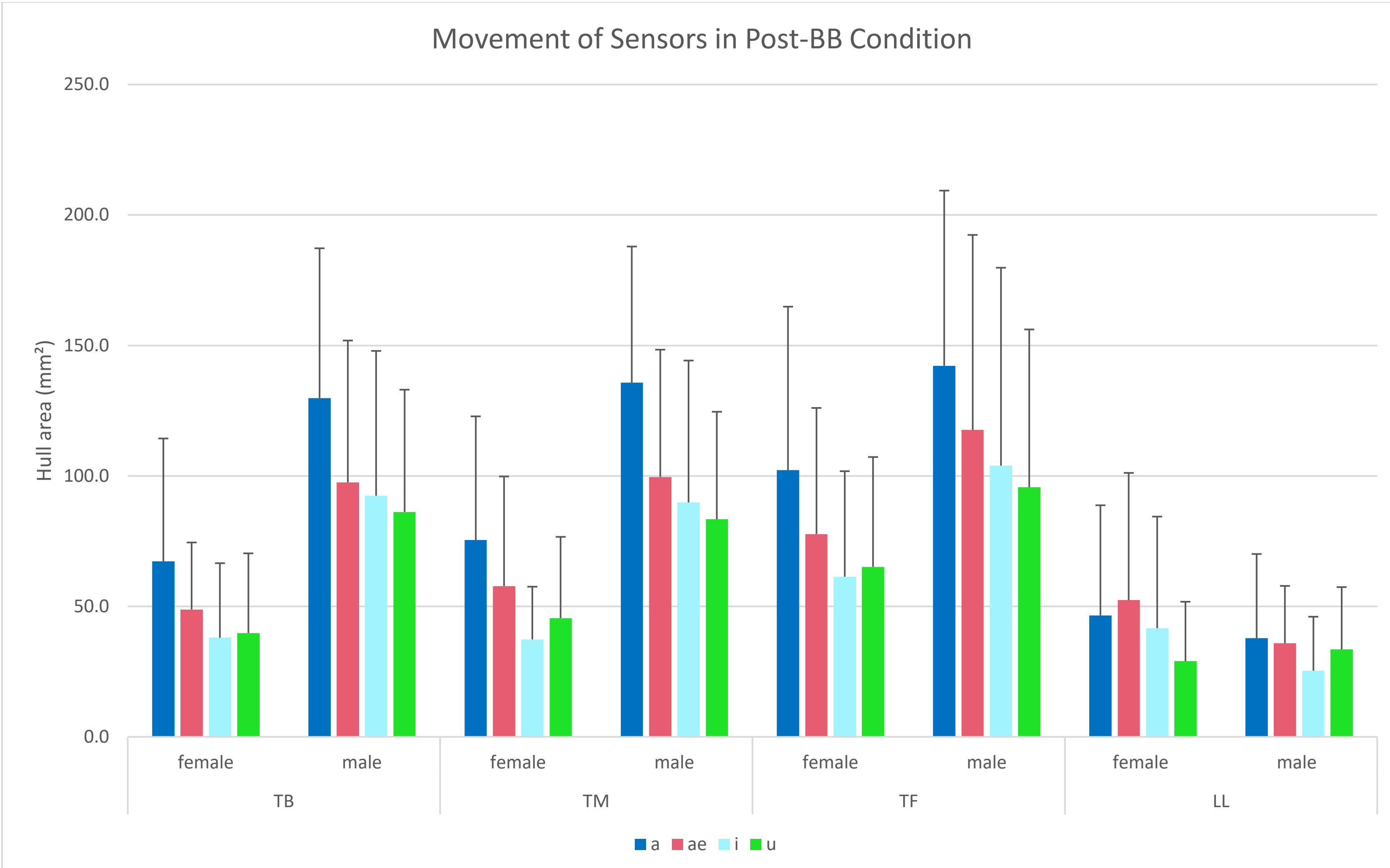

Figure 4. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 6

Jaw Movement Concurrent Contrasts Differences Between Vowels When Compared to /a/

		/æ/		/i/		/u/	
		F	*p*	*F*	*p*	*F*	*p*
Pre-BB							
	TB	5.534	0.033	27.428	<0.001	12.294	0.003
	TM	5.406	0.035	28.840	<0.001	13.110	0.003
	TF	5.187	0.038	28.406	<0.001	13.123	0.003
	LL	4.331	0.055	27.166	<0.001	12.412	0.003
Post-BB							
	TB	1.108	0.309	0.113	0.741	0.139	0.715
	TM	0.933	0.349	0.137	0.716	0.136	0.717
	TF	0.922	0.352	0.148	0.706	0.151	0.703
	LL	0.876	0.364	0.182	0.676	0.214	0.650

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 7

One-Way ANOVA - Jaw Movement Differences Between Gender for Each Vowel

		/ɑ/			/æ/			/i/			/u/		
		df	*F*	*p*	df	*F*	*p*	df	*F*	*p*	df	*F*	*p*
Pre-BB													
	TB	1	0.217	0.648	1	2.947	0.107	1	1.707	0.211	1	0.108	0.747
	TM	1	0.031	0.862	1	1.535	0.234	1	1.286	0.275	1	0.008	0.929
	TF	1	0.009	0.924	1	1.175	0.296	1	1.170	0.297	1	<0.001	0.993
	LL	1	0.014	0.908	1	0.785	0.390	1	0.755	0.399	1	0.064	0.804
Post-BB													
	TB	1	1.033	0.326	1	4.66	0.047	1	1.189	0.293	1	0.784	0.390
	TM	1	0.788	0.389	1	4.326	0.055	1	0.916	0.354	1	0.477	0.052
	TF	1	0.749	0.400	1	4.196	0.058	1	0.864	0.367	1	0.423	0.525
	LL	1	0.668	0.426	1	3.892	0.067	1	0.759	0.397	1	0.358	0.559

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 8

Hull Area of the Movement of Jaw in mm² for Pre-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	14.1	6.9	19.4	5.0	9.5	6.4	8.6	4.7
	TM	15.4	7.3	21.4	5.5	10.5	7.1	9.4	5.2
	TF	17.3	8.5	23.9	6.6	11.6	7.8	10.5	5.6
	LL	22.4	11.1	30.8	8.5	15.0	9.8	13.4	7.0
Male									
	TB	12.5	6.9	14.7	6.1	6.0	4.3	7.8	4.4
	TM	14.8	8.0	17.5	7.4	7.1	4.9	9.2	5.0
	TF	16.9	9.1	19.9	8.3	8.1	5.5	10.5	5.5
	LL	23.2	13.9	26.7	10.2	11.2	8.2	14.3	7.9

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

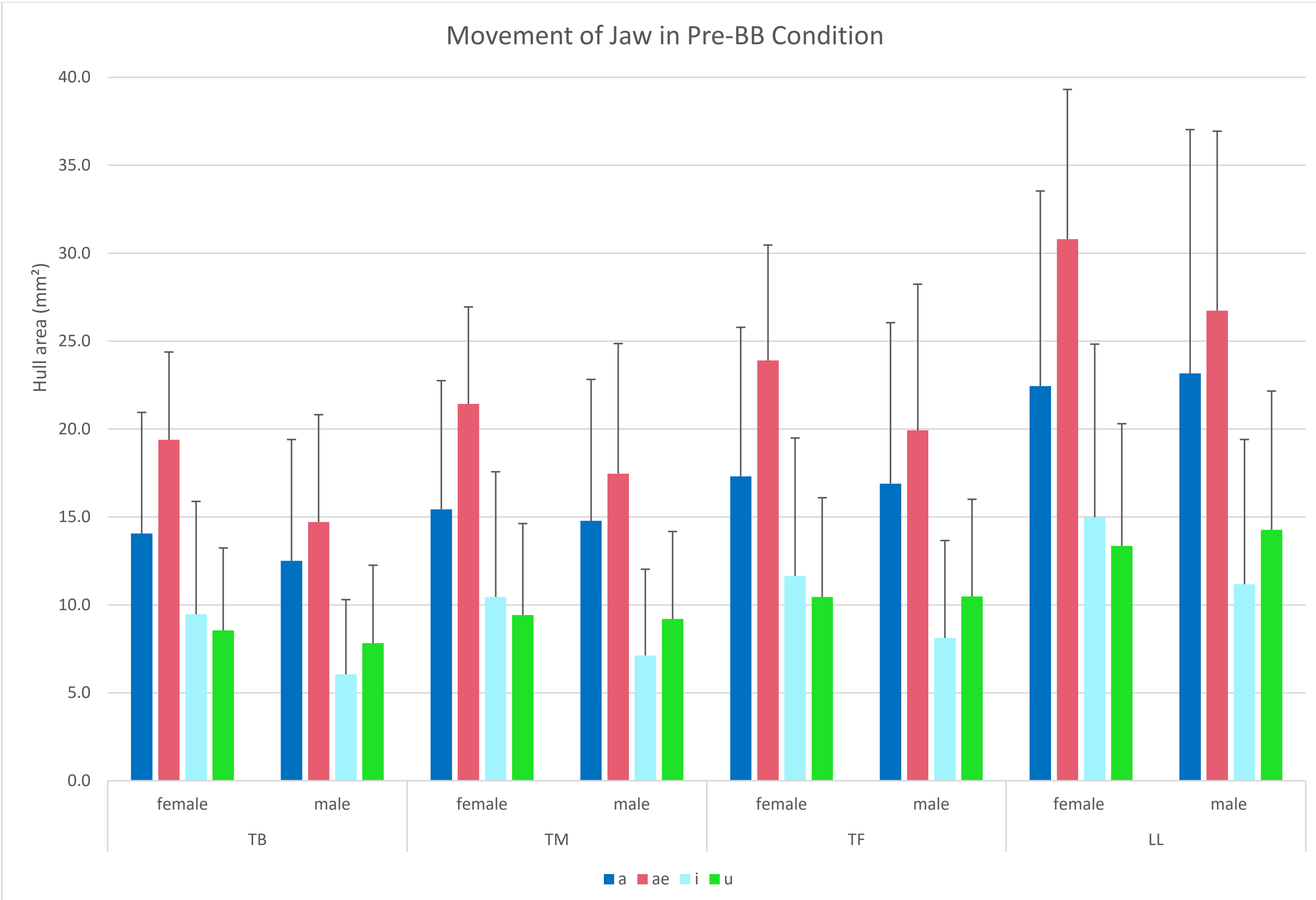

Figure 5. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 9

Hull Area of the Movement of Jaw in mm² for Post-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	5.8	7.6	9.2	10.0	5.7	6.7	5.1	5.0
	TM	6.5	8.7	10.2	11.2	6.3	7.6	5.7	5.7
	TF	7.3	9.6	11.4	12.7	7.0	8.5	6.3	6.3
	LL	9.7	13.3	15.2	17.4	9.3	11.5	8.3	8.6
Male									
	TB	3.1	2.6	2.0	1.2	3.0	2.9	3.3	3.5
	TM	3.8	3.4	2.4	1.5	3.6	2.6	4.0	4.6
	TF	4.3	3.8	2.7	1.7	4.1	4.1	4.5	5.1
	LL	5.8	5.0	3.7	2.3	5.6	5.5	6.1	6.6

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

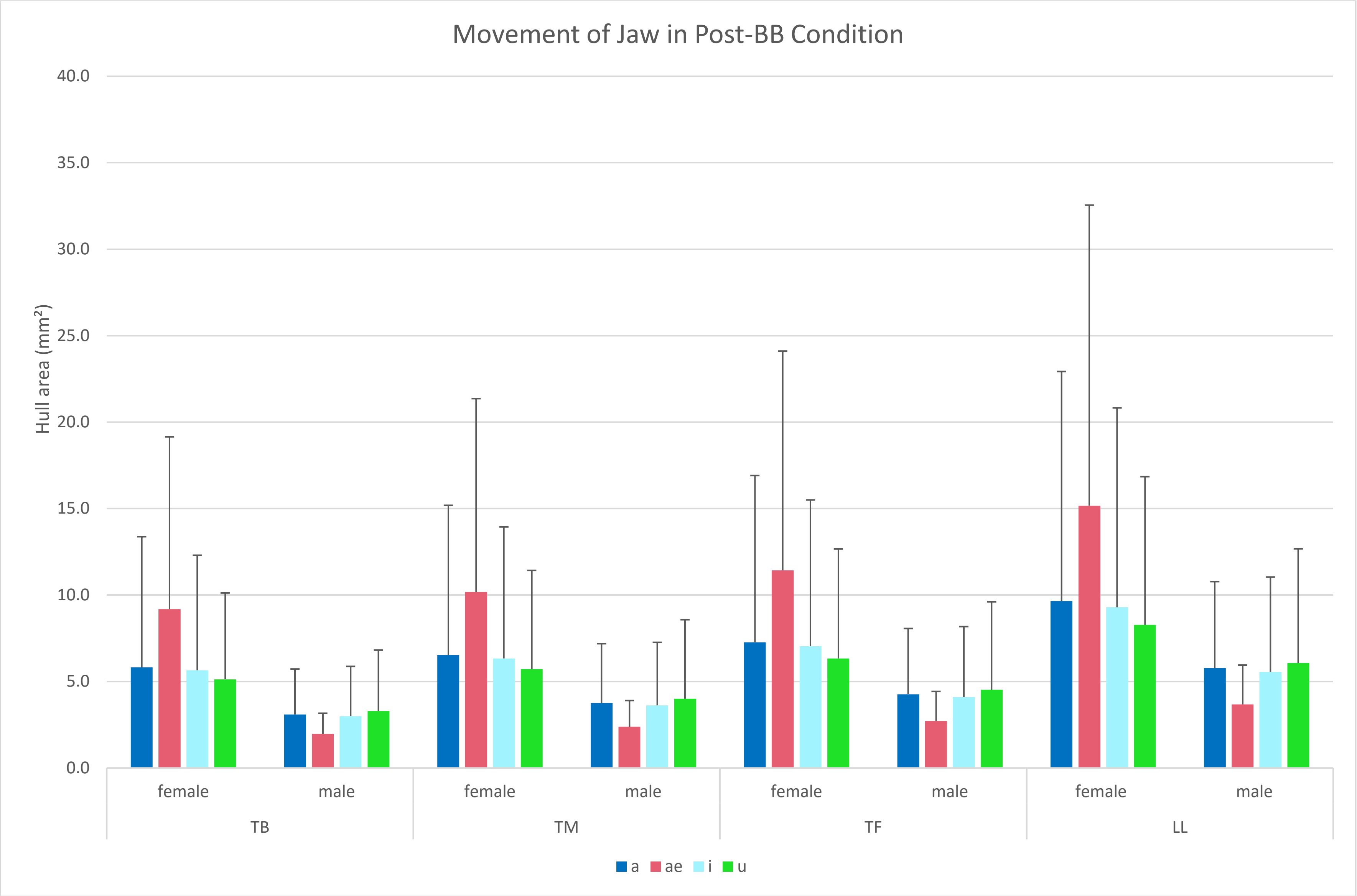

Figure 6. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 10

Sensor/Jaw Ratio Concurrent Contrast Differences Between Vowels When Compared to /a/

		/æ/		/i/		/u/	
		F	*p*	*F*	*p*	*F*	*p*
Pre-BB							
	TB	16.292	0.001	2.655	0.124	0.550	0.470
	TM	12.927	0.003	0.626	0.441	0.585	0.456
	TF	8.468	0.011	1.343	0.265	0.762	0.396
	LL	1.439	0.249	2.578	0.129	3.276	0.090
Post-BB							
	TB	1.858	0.193	6.942	0.019	14.131	0.002
	TM	1.920	0.186	3.624	0.076	8.743	0.010
	TF	0.842	0.373	4.647	0.048	8.357	0.011
	LL	<0.001	0.998	0.684	0.421	0.972	0.340

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 11

One-Way ANOVA - Sensor/Jaw Ratio Differences Between Genders for Each Vowel

		/ɑ/			/æ/			/i/			/u/		
		df	*F*	*p*	df	*F*	*p*	df	*F*	*p*	df	*F*	*p*
Pre-BB													
	TB	1	12.193	0.003	1	25.634	<0.001	1	18.306	0.001	1	6.970	0.019
	TM	1	5.184	0.038	1	10.218	0.006	1	5.703	0.031	1	3.154	0.096
	TF	1	7.030	0.018	1	10.157	0.006	1	4.191	0.059	1	3.882	0.068
	LL	1	1.053	0.321	1	1.132	0.304	1	1.723	0.209	1	1.321	0.268
Post-BB													
	TB	1	1.122	0.306	1	5.467	0.034	1	10.426	0.006	1	0.816	0.381
	TM	1	0.660	0.429	1	4.196	0.058	1	4.776	0.045	1	1.101	0.311
	TF	1	0.032	0.860	1	2.771	0.117	1	0.864	0.367	1	0.146	0.708
	LL	1	0.795	0.387	1	0.042	0.840	1	0.027	0.871	1	0.054	0.819

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Table 12

Ratio of Sensor Movement to Jaw Movement in Pre-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	7.6	2.6	4.5	1.1	5.6	1.8	7.5	5.0
	TM	7.4	3.2	4.5	1.4	5.3	1.9	7.5	5.6
	TF	7.6	3.2	5.2	1.6	5.8	2.3	8.1	6.3
	LL	2.4	1.8	2.5	2.0	2.6	1.7	3.1	1.9
Male									
	TB	15.3	5.8	10.0	2.9	25.5	13.1	13.9	5.0
	TM	14.1	7.8	9.5	4.2	22.0	19.6	12.5	5.8
	TF	11.8	3.3	9.1	3.1	23.8	24.7	13.3	4.5
	LL	4.2	4.9	4.8	5.9	9.1	13.7	7.9	11.5

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

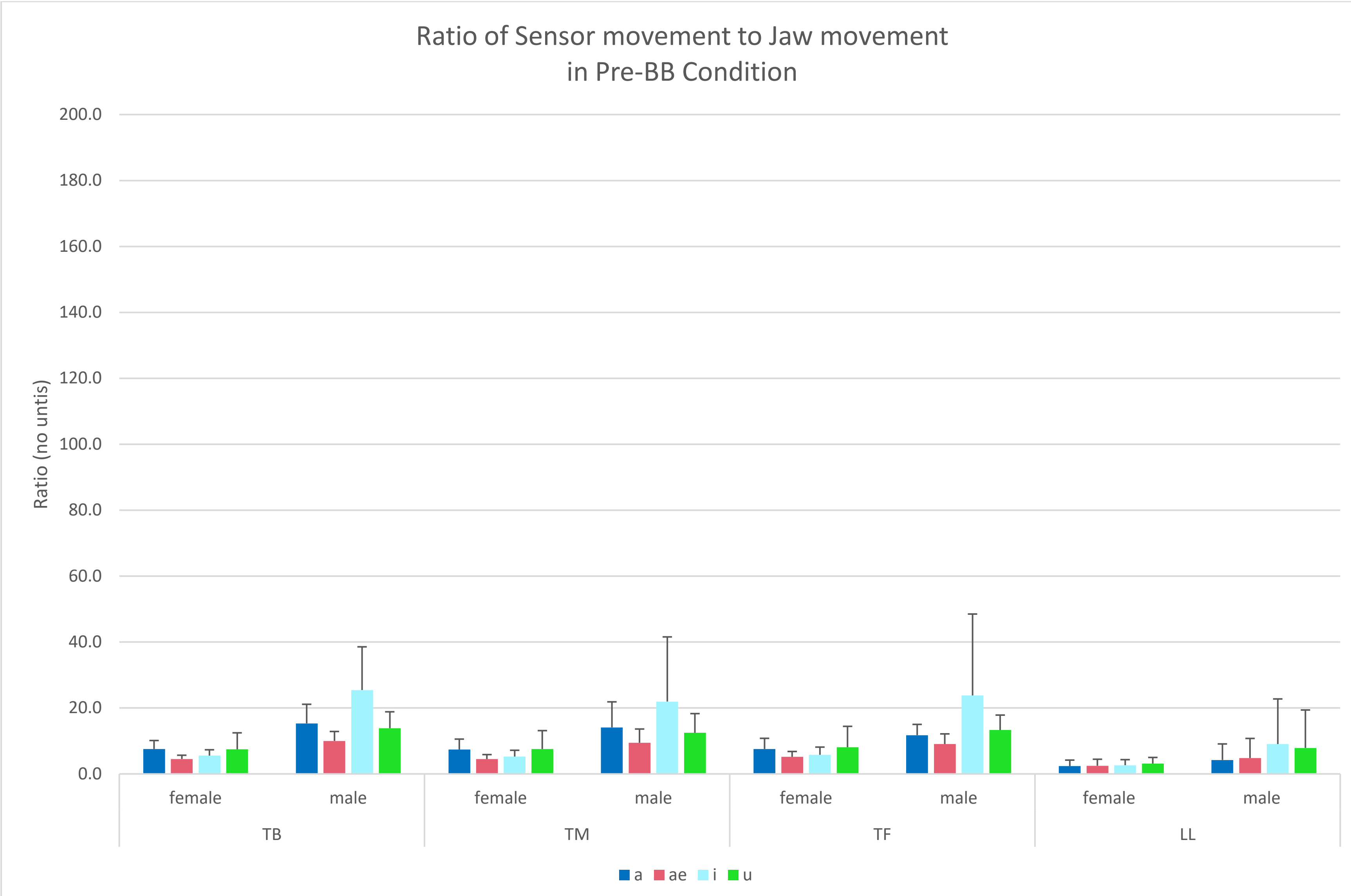

Figure 7. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 13

Ratio of Sensor Movement to Jaw Movement in Post-BB Condition

		/ɑ/		/æ/		/i/		/u/	
		Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Female									
	TB	69.7	70.8	43.5	41.3	23.7	20.9	39.1	36.1
	TM	68.8	82.6	38.8	42.8	19.2	16.8	33.9	33.8
	TF	77.5	87.1	46.9	47.5	27.5	23.8	40.8	37.9
	LL	32.2	66.5	24.0	45.1	18.0	32.6	16.9	27.5
Male									
	TB	108.1	77.7	89.4	39.6	74.7	40.0	57.8	47.2
	TM	99.5	73.1	86.8	52.4	80.1	76.9	57.7	55.4
	TF	83.5	45.4	87.9	53.3	65.8	54.0	47.9	39.3
	LL	12.3	9.5	20.6	19.9	15.7	24.3	14.3	17.8

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

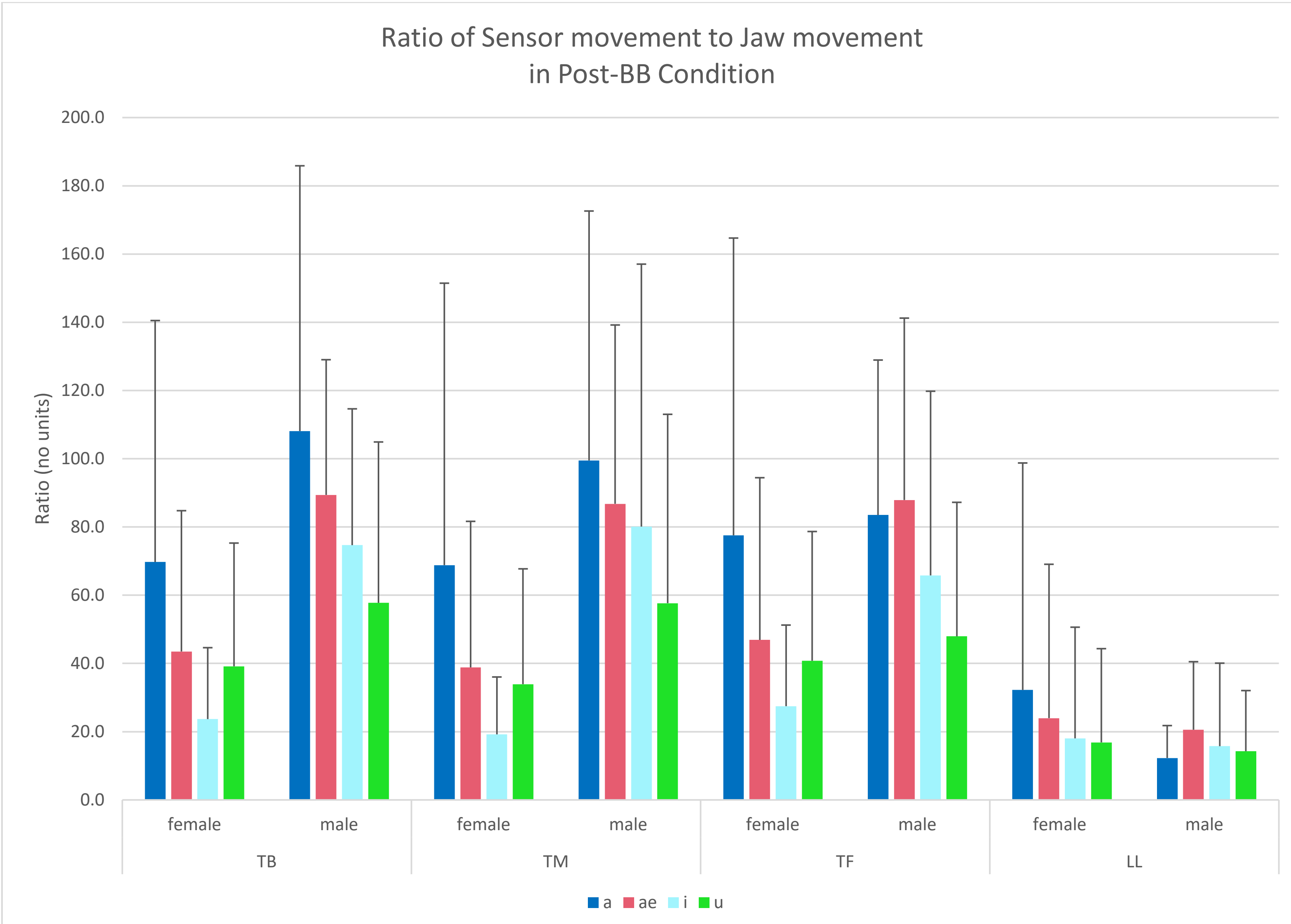

Figure 8. Mean and standard deviations of the sensor hull area for each vowel separated by gender and sensor positions.

Table 14

Repeated Measures ANOVA Within-Subjects Effects: Pre-BB vs. Post-BB for Each Sensor

	/ɑ/			/æ/			/i/			/u/		
	df	*F*	*p*	df	*F*	*p*	df	*F*	*p*	df	*F*	*p*
TB	1	3.672	0.084	1	9.231	0.013	1	1.906	0.197	1	0.015	0.905
TM	1	8.240	0.017	1	15.933	0.003	1	2.813	0.124	1	0.361	0.562
TF	1	8.109	0.017	1	14.255	0.004	1	1.459	0.255	1	0.463	0.512
LL	1	0.837	0.382	1	2.136	0.175	1	0.243	0.632	1	0.909	0.363

Note. TB = tongue back; TM = tongue mid; TF = tongue front; LL = lower lip

Motor Equivalence Results- Hull Areas and Ratios for /ɑ/

The mean hull area was calculated for the five productions of the nonsense /ɑ/ phrase (i.e., /eɪ͜ərɑ/) for the tongue front (TF) sensor for each participant. Increased tongue movement (Sensor) for the Post-BB condition, when compared to Pre-BB condition, was seen for F1, F10, M3 and M8, while all participants decreased jaw movement when the bite block was in place (see Table 15 and Figures 9-10). Jaw movement decreased for all speakers in the Post-BB condition (see Table 15 and Figures 11-12). The Ratio between the Sensor and Jaw movements increased overall for the Post-BB condition (see Table 15 and Figures 13-14). F2, F3, F7, M4 and M6 were excluded from this part of the analysis due to their being substantial outliers (>10 mm^2 larger hull areas in the Post-BB condition compared to other speakers). These outliers led to the conclusion that these participants inconsistently clamped down on the bite blocks throughout the data collection and thus their Post-BB data did not reflect a true bite block condition.

The Post-BB Ratio was the largest for F4, F10, M10 and M8. F1 Post-BB Ratio increased as a result of the Post-BB Sensor movement only decreasing 0.4 mm^2, but the Jaw movement decreased by 16.9 mm^2 once the bite block was inserted. M10 Post-BB Ratio increased as a result of the Sensor hull area decreasing by 40.6 mm^2 once the bite block was inserted, while the Post-BB Jaw movement for M10 decreased by 15.7 mm^2. F10 Post-BB Ratio increased as a result of the Post-BB Sensor movement increasing by 5.9 mm^2, while the Jaw movement decreased by 7.6 mm^2 once the bite block was in place. M8 Post-BB Ratio increased as a result of the Post-BB Sensor increasing by 6.3 mm^2, while the Jaw decreased in the Post-BB condition by 10.4 mm^2 (See Table 15).

M1, M2, M3 and M9 Post-BB Ratios were larger than F1, F6, F9 and M7 Post-BB Ratios (See Table 15 and Figures 13-14). The Ratios differed due to different Pre-BB Sensor hull areas, as well as Sensor hull area increases or decreases from Pre-BB to Post-BB condition. The M1 Pre-BB Sensor large hull area decrease of 67.1 mm^2, as well as the decrease of 16.4 mm^2 for the Jaw movement resulted in the larger Post-BB Ratio (See Table 15 and Figures 13-14). The M2 Pre-BB Sensor hull area decrease of 73.3 mm^2, as well as the Jaw movement decrease of 10.1 mm^2 resulted in a larger Post-BB Ratio. The M9 Pre-BB Sensor hull area had a large decrease of 59.1 mm^2, as well as a Jaw decrease of 11 mm^2 resulted in a larger Post-BB Ratio. On the other hand, the M3 Post-BB Ratio increased by 12 mm^2 for Sensor movement, while the Jaw area decreased by only 2.8 mm^2.

The participants with the smallest Ratios (i.e., F1, F6, F9, M7) had the largest Pre-BB Jaw movements and/or the smallest difference between Pre-BB Jaw movements and Post-BB Jaw movements. F1 Sensor movements had relatively no change once the bite block was inserted, but the Jaw movement decreased by 17 mm^2. F6 Sensor movements had a large decrease of 71.4 mm^2 while the Jaw movement for the Pre-BB was very large and then decreased by 23.6 mm^2. F9 Sensor movements decreased by 14 mm^2 while the Jaw movements only decreased by 3.6 mm^2 (See Table 15). M7 had a relatively large Post-BB jaw movement and a relatively large Post-BB Sensor movement which resulted in the smallest Sensor/Jaw Ratio.

Table 15

Tongue Front Movement in mm² During The /ɑ/ Phrase For Each Participant

Participants	Pre-BB Sensor	Post-BB Sensor	Pre-BB Jaw	Post-BB Jaw	Pre-BB Ratio	Post-BB Ratio
F1	93.9	— 93.5	19.2	↓ 2.2	5.7	↑ 54.2
F4	50.9	↓ 35.3	9.4	↓ 1.7	7.7	↑ 241.6
F6	126.3	↓ 54.9	26.3	↓ 2.7	4.9	↑ 26.1
F9	56.0	↓ 41.1	6.8	↓ 3.2	8.9	↑ 23.4
F10	104.7	↑ 110.6	8.9	↓ 1.3	13.4	↑ 183.3
M1	154.2	↓ 87.2	17.8	↓ 1.4	9.2	↑ 79.0
M2	203.1	↓ 129.8	12.2	↓ 2.1	17.9	↑ 82.5
M3	44.2	↑ 56.1	4.1	↓ 1.3	13.8	↑ 75.6
M7	145.3	↓ 118.5	15.6	↓ 7.8	9.7	↑ 55.7
M8	128.2	↑ 134.5	11.9	↓ 1.5	11.3	↑ 121.7
M9	210.9	↓ 151.8	13.9	↓ 2.9	15.4	↑ 80.8
M10	189.8	↓ 149.2	18.2	↓ 2.5	11.3	↑ 178.2

Note. ↓ = decrease hull area movement in mm² from the Pre-BB to the Post-BB condition.
↑ = increase hull area movement in mm² from the Pre-BB to the Post-BB condition.
— = < 10% difference from the Pre-BB to the Post-BB condition.

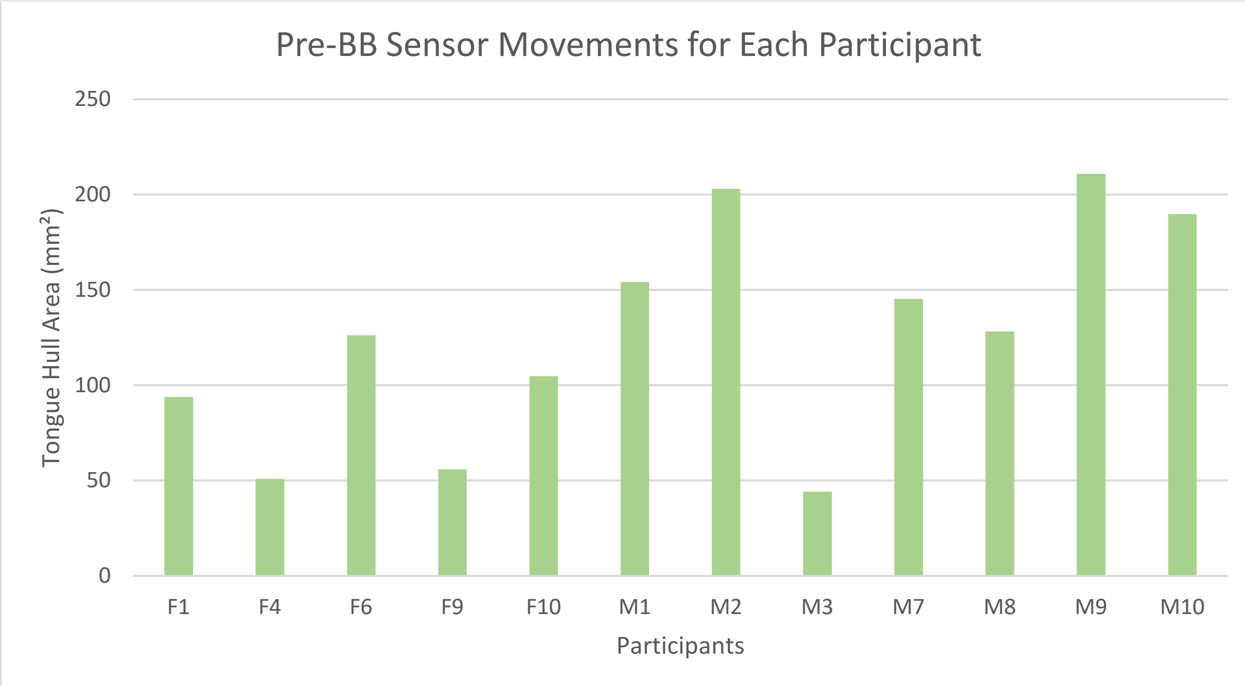

Figure 9. Male (M) and Female (F) participants' Sensor hull areas for the front tongue location.

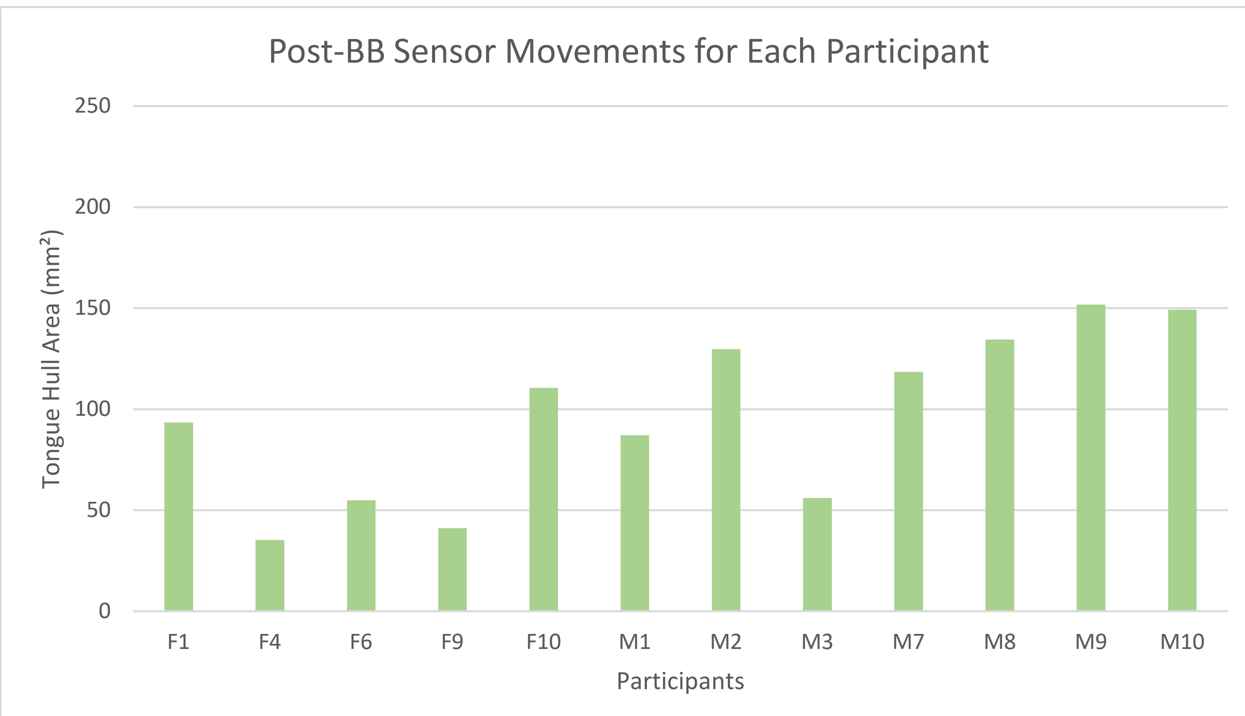

Figure 10. Male (M) and Female (F) participants' Sensor hull areas for the front tongue location.

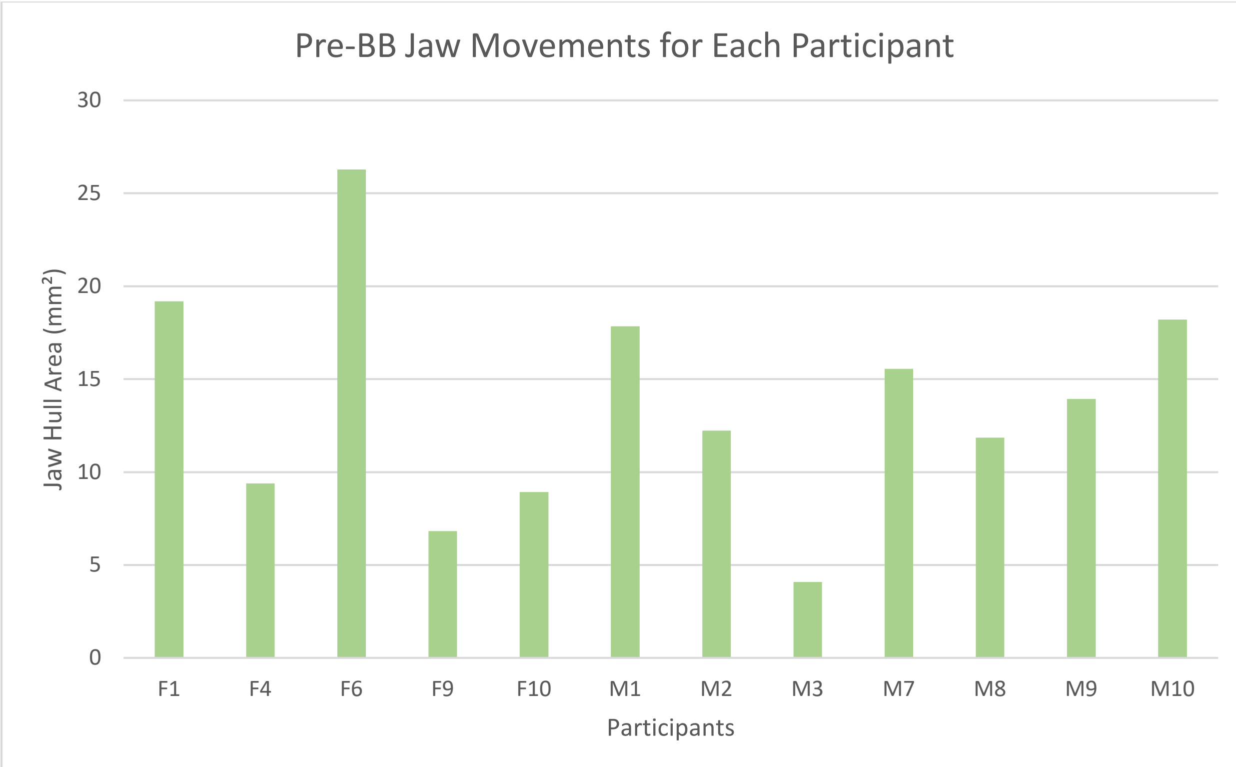

Figure 11. Male (M) and Female (F) participants' Jaw hull areas for the front tongue location.

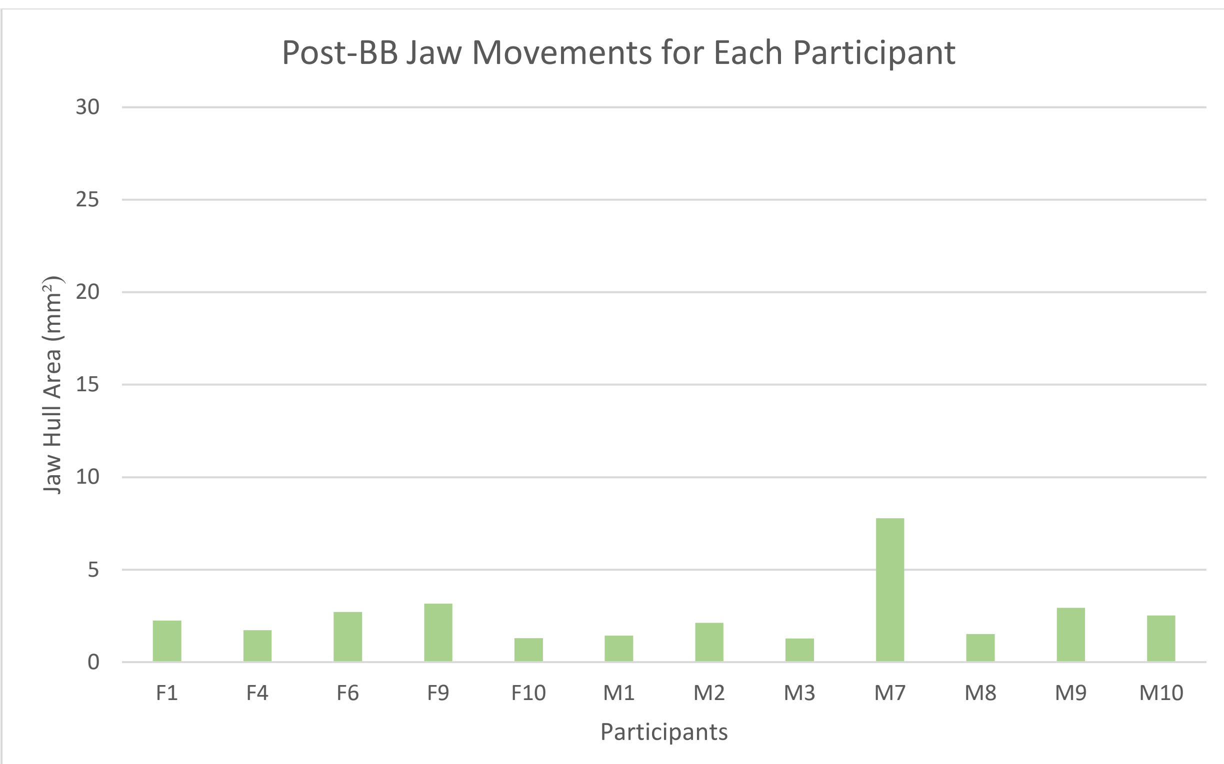

Figure 12. Male (M) and Female (F) participants' Jaw hull areas for the front tongue location.

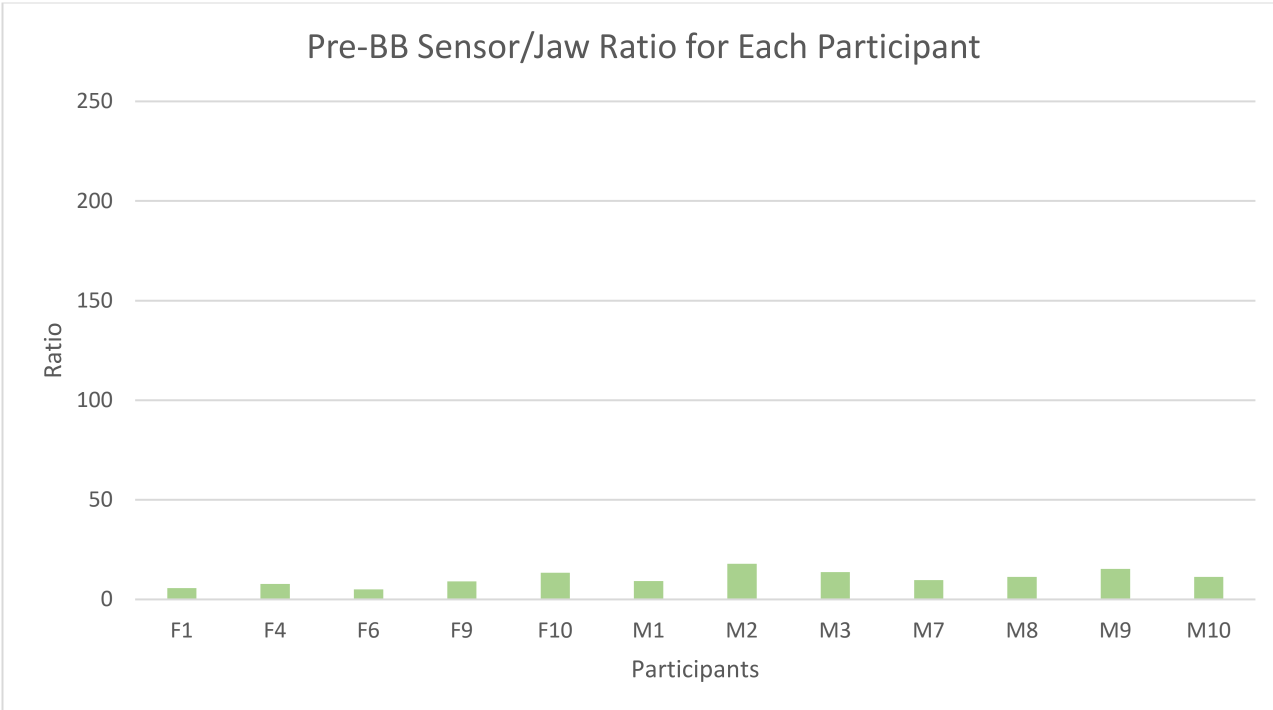

Figure 13. Male (M) and Female (F) participants' Sensor/Jaw hull area Ratios for the front tongue location.

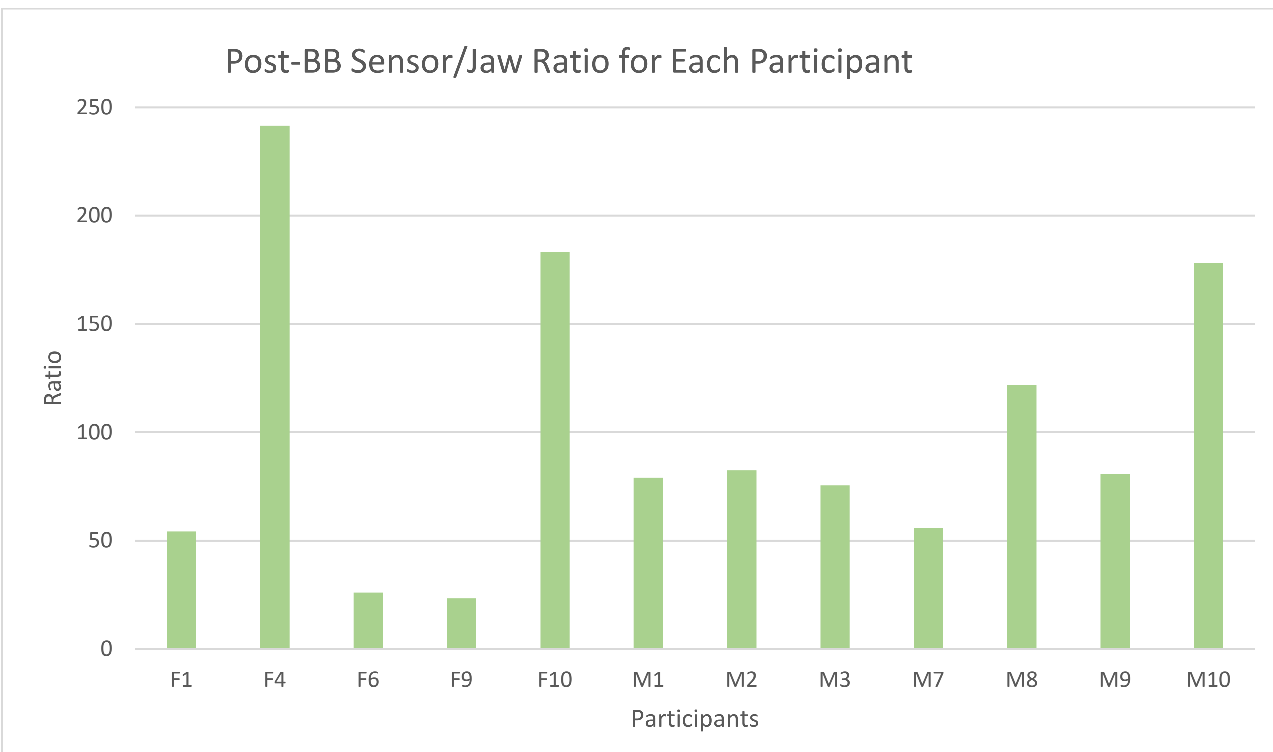

Figure 14. Male (M) and Female (F) participants' Sensor/Jaw hull area Ratios for the front tongue location.

Discussion

This study examined kinematic differences between speakers during adaptation to a bite block. Kinematic differences were observed across vowel phrases and between genders. These differences provided evidence that participants used a variety of motor equivalence strategies during speech production.

Vowel Differences

It was hypothesized that there would be differences in the hull areas and ratios across vowels for all participants. Each vowel phrase (i.e., /æ/, /i/, /u/), when compared to the /ɑ/ phrase, showed differences in the hull area of the tongue and the jaw. These differences demonstrate differences in articulatory activity between vowels as well as between participants.

The differences in the hull areas and ratios for each vowel differed between males and females. Changes were also observed between conditions (i.e., Pre-BB and Post-BB). Overall, the Sensor movement of the tongue (i.e., TB, TM, TF) was largest for the /ɑ/ phrase in both conditions. The /æ/ phrase had the next largest Sensor movements for both males and females in the Pre-BB condition. There were larger movements for the low back vowel /ɑ/ versus the low front vowel /æ/. On the other hand, /i/ and /u/, both being high vowels, showed different patterns between males and females. For females, /i/ was slightly larger for the TB than /u/, while /u/ was slightly larger for TM and TB and males had a larger /i/ for all tongue Sensors in the Pre-BB condition. For the Post-BB condition, /u/ had larger movements for /i/ for TF for females and all tongue Sensors for males.

Lee, Shaiman, and Weismer (2016) examined consonant vowel consonant structure (CVC) words containing one of the four corner vowels (i.e., /ɑ, æ, i, u/) with an electromagnetic articulograph recording tongue positions using three sensors which were glued to the tongue (i.e., tongue dorsum, tongue body, tongue tip). Acoustic data were gathered in order to collect simultaneous data for tongue positions and formant frequencies. Tongue movements depended on consonants surrounding the vowels. For example, /ɑ/ and /æ/ tongue positions were less low and /æ/ was less forward in /dVd/ when compared to /hVd/. The results of the study by Lee et al. led to the conclusion that vowels change due to coarticulatory effects. As a result of the findings by Lee et al., if a speaker's vowel productions change due to the particular sounds that surround them, then vowel production would also be sensitive to change when a perturbation is introduced. In the current study, the findings showed that perturbation, in the form of a bite block, impacted the articulatory movements of vowel production depending on the speaker and the vowel phrase being produced.

A study conducted by Kelso et al. (1984) examining perturbation found 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 the ones found in unperturbed speech. Similarly, the current study found that the tongue compensated for the stabilization of the jaw from the introduction of the bite block. The overall hull area of the Sensor decreased in the Post-BB condition with exceptions of females' TF /ɑ/, TF /i/, and TM /u/ and TF /u/. The hull area for the Sensor decreased in the Post-BB condition for males, with exceptions for TB and TM for /u/. We would expect to see a greater Ratio of tongue to jaw movements as a result of the tongue making up for the reduced jaw contribution. When the jaw was stabilized, decreased Sensor movements may have resulted from the jaw contributing less to the articulatory movements overall, due to the bite block. The Sensor hull area would decrease, even though the ratio shows significant changes.

The current study found significant differences for each phrase ending in the different vowels (i.e., /æ/, /i/, /u/) when compared to the phrase ending in /ɑ/ for Sensor in the Pre-BB and Post-BB conditions. /æ/ (low front vowel) had smaller movements than /ɑ/ (low back vowel) for TB in the Pre-BB condition and TB and TM in the Post-BB condition. /i/ (high front vowel) had smaller tongue movements than /ɑ/ (low back vowel) for TB, TM, and TF in the Pre-BB and Post-BB conditions. /u/ (high back vowel) had smaller movements than /ɑ/ (low back vowel) for TB, TM, and TF in both conditions. These findings show that the low back vowel /ɑ/ creates the largest tongue movements. Previous investigations have not compared kinematic vowel hull areas in this way, but McFarland and Baum (1995) examined perturbation acoustic effects on vowels and found that /ɑ/ was impacted the most by the large bite block of 22.5 mm which was unexpected due to /ɑ/ usually being produced with a larger open oral cavity. The current study and McFarland and Baum showed different ways the /ɑ/ was impacted by the perturbation, but McFarland and Baum made no comparisons between vowels.

Perkell et al. (1993) provided evidence for differences in jaw and lip contributions to speech production when no perturbation was present. When the jaw was stabilized, the lower lip compensated with increased movements in order to achieve oral closure. As a result of the oral closure being completed by the lower lip, accurate speech output was achieved. These differences in jaw and lip contributions were also observed in the current study. The lower lip showed no significant vowel-related differences (i.e., /ɑ/ did not differ from /æ/, /i/ or /u/) in the Post-BB condition, likely because the stimuli contained no bilabial consonants. When the bite block was in place, the jaw was stabilized which caused the tongue to change movement patterns in order to achieve accurate speech production. The vowel phrase for /æ/ showed significant differences from Pre-BB to Post-BB for the TM and TF hull areas. This decrease in movement extent from Pre-BB to Post-BB was probably due to the bite block preventing the amount of jaw lowering needed to produce this low front vowel. Any compensation by way of increased TM and TF movements would be insufficient to make up for what is usually a large contribution from the jaw.

No significant differences for the main effects for vowels were found in the Post-BB condition for the Jaw. This was expected due to the bite block stabilizing the jaw. The Jaw movements were similar due to the fact that there should be no, or minimal, movement with the bite block in place. If the participant did not bite down consistently during the Post-BB condition throughout the data collection, the jaw was not accurately stabilized. In such cases, the participants were removed from this part of the analysis.

When comparing the vowel phrases for /æ/, /i/ and /u/ to the vowel phrase for /ɑ/, the vowels /æ/ and /u/ had significantly smaller Jaw movements than /ɑ/ in the Pre-BB condition. In the Post-BB condition, no significant differences were found for /æ/, /i/ and /u/ when compared to the vowel phrase for /ɑ/. These findings show that Jaw movements differed greatly between vowels when the jaw was free, but not when the jaw was stabilized, as would be predicted in a bite block condition that tethered the jaw in one position.

The Ratio metric for the main effect differences across vowels was only significant in the Post-BB condition for the TB Sensor movements. Since the TMJ and the tongue back sensor were relatively close to one another, the contribution of the jaw to the movement of tongue back increased (Westbury et al., 2002).

Gender Differences

A study previously completed by Mohsenin (2003) found differences in oropharyngeal and pharyngeal sizes between genders, and as such, showed significantly smaller structures for females as compared to males. Consistent with these findings, it was taken into consideration that the size of each articulator (i.e., the participants' lips, tongue, jaws) would differ between genders. This knowledge led to the hypothesis that differences in articulator size would result in differences between genders for the hull areas. The results from the current study showed larger hull areas for males when compared to females for the Sensor metric, but not the Jaw metric.

The majority of the male participants (i.e., M1, M2, M7, M8, M9, M10) had larger TF Pre-BB Sensor movements for the /ɑ/ phrase. The participant F6 had slightly smaller hull area movements (i.e., 2 mm^2 smaller) than M8. All of the other female participants (i.e., F1, F4, F9, F10) had smaller movements than F6, with participant M3 having the smallest TF Sensor movements overall. These findings provide additional evidence that most males make larger articulatory movements than females.

Motor Equivalence

Motor equivalent responses were observed in the current study. Results demonstrated that the participants changed their articulatory patterns in order to achieve accurate speech production when the bite block was inserted. Kulak Kayikci et al. (2012) found that any oral appliance or perturbation can cause differences in speech production, which was also found in the current study when the bite block was in place.

Different motor equivalent tongue movement strategies were observed in order for each participant to produce the /ɑ/ phrase. The first motor equivalent tongue movement strategy was observed for participants F1, F10, M3 and M8, who increased their tongue front movement from Pre-BB to Post-BB. This was an expected effect of the perturbation because when the jaw was stabilized the tongue and the lips increased movements in order to achieve accurate speech (Hughes & Abbs, 1976; Perkell, et al., 1993). The second motor equivalent tongue movement strategy was observed for participants F4, F6, F9, M1, M2, M7, M9 and M10, who decreased their tongue front movements from Pre-BB to Post-BB. As a result of the perturbation, participants' jaw stabilization resulted in reduced tongue movements in these speakers. These speakers did not overcome the jaw limitations like the speakers (i.e., F1, F10, M3, M8) mentioned above (Kulak Kayikci et al., 2012).

As a result of each speaker producing the /ɑ/ phrase differently, motor equivalent strategies were observed. M9 produced the largest tongue Sensor movements for both the Pre-BB and Post-BB conditions compared to all other participants, but did not produce the largest Jaw movements. Due to the fact that the hull area of the Jaw movements for M9 fell in the middle of all other participants, the Ratio of M9 was not the largest. The results from participant M9 demonstrated that even though a speaker's tongue movements were large, it does not necessarily mean that their jaw movements were also large. This provided additional evidence that motor equivalent articulatory differences exist across speakers (Hughes & Abbs, 1976).

Westbury, Severson, and Lindstrom (2000) explored articulator movements by gluing small gold pellets (radio-opaque sensors) on the tongue blade and the tongue dorsum, at the vermillion border of each lip and at the incisors. The sensors tracked movements with an x-ray microbeam system on the x and y coordinates as the participants produced the words *special* and *problem*, specifically analyzing the initial vowel consonant structure (VC) transition (i.e., /ɛʃ/, /ɑb/). Westbury et al. (2000) found that the sequencing of the jaw and tongue movements between participants were comparable, but not exactly the same. This showed that speakers do not have to move the articulators in the same way to create the same speech output.

The current study found equivalent differences between participants as found by Westbury et al. (2000). Participant M3 produced the smallest tongue movements in the Pre-BB condition, while F4 produced the smallest tongue movements Post-BB. M3 increased tongue Sensor movements in the Post-BB condition, while F4 decreased tongue Sensor movements Post-BB. As a result of the tongue movement increasing for M3 and decreasing for F4, and varying Jaw movements, the Ratios for M3 and F4 differed. F6 produced the largest Pre-BB Jaw movement, but the third largest Post-BB Jaw movement, while M7 produced the largest Post-BB Jaw movement, but the fifth largest Pre-BB Jaw movement. Slight Jaw movements were observed Post-BB, in spite of the bite block. This was likely due to slight compression of the bite block material or minor loosening of the grip between the molars. These movements were not large enough to be excluded from the BB analysis. Variations were present within each participant and across participants. This showed individual differences in compensating for the presence of the bite block.

Another aspect examined within the /ɑ/ phrase was the amount of decrease, in mm^2, from Pre-BB to Post-BB for the tongue front Sensor and Jaw movements. For the males, the largest difference for tongue front Sensor movement was observed for M2 from Pre-BB to Post-BB while the smallest difference between Pre-BB and Post-BB was for participant M8. For the females, the largest difference for tongue front Sensor movement was observed for F6 while F1 had the smallest difference. Additionally, for the Jaw movements, F9 had the smallest difference between Pre-BB Jaw movement and Post-BB Jaw movement. All participants decreased Jaw movements in the Post-BB condition. Gender differences alone do not account for the variations of the Sensor and Jaw movements observed when the bite block was in place. Both males and females had a large range of movement decreases or increases for Post-BB. This provided strong evidence towards the existence of motor equivalence. Hughes & Abbs (1976) found that the degree to which motor equivalence exists is subject-dependent. This subject-dependent aspect of motor equivalence was also found in the current study.

Limitations of Current Study and Further Research

The analysis of the stimulus phrases in the present study resulted in some limitations regarding exact segmentation of the /r/. The hull area for the data were calculated for the individual nonsense words /e͜ɪərɑ/, /e͜ɪəræ/, /e͜ɪəri/, and /e͜ɪəru/. The analysis of these nonsense stimulus words (rather than analyzing /r/ directly) resulted in more global, phrase level measures (hull areas) as opposed to gesture-specific measures like displacement and peak velocity, which are common in kinematic work.

An unanticipated limitation was discovered when analyzing the data for the presence of motor equivalence. Some participants inconsistently bit down on the bite block which varied by utterance. The amount of jaw stabilization was therefore not constant 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 not to allow the jaw to loosen during speech production.

Another limitation of the current study was a smaller number of participants (N) than initially anticipated. Due to tracking errors of some sensors during data collection, three participants' data could not be used for analysis. Additionally, the participants who did not keep bite blocks firmly in place had to be excluded from analysis of the motor equivalence results. As a result, the N decreased from 20 participants to 17 for the repeated measures ANOVA and the one-way ANOVA, and 12 for the motor equivalence analyses.

The current study gathered data regarding the initial response to a perturbation. Further analyses of this data set could explore the adaptation patterns over time. This will provide additional information about the articulators and how speakers adapt differently to the presence of the bite block over time. The coordination between articulators can also be explored further.

Conclusion

This study examined the motor equivalent strategies used following a perturbation, as well as articulatory kinematic differences between genders, among participants and across vowel phrases. It is important to consider each individual's speaking patterns prior to bite block insertion. Pre-BB articulatory coordination strategies might result in greater differences between participants once the bite block is inserted. The findings of the current study have potential clinical implications for the treatment of speakers in a rehabilitation setting. Intervention for speech and language disorders is not a "one size fits all" treatment. Many variables need to be taken into consideration when deciding the treatment plan for each individual patient or client. In order to provide effective therapy, the differences between individuals' articulatory strategies could be considered in order to maximize an individual's progress in therapy.

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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 Hearing Research, 54*(3), 727-739. doi:10.1044/1092-4388(2010/09-0256)

Objective: The purpose of this study was to determine why some speakers use motor equivalence and others do not. *Method:* The subjects for this study were three men and four women, aged 25-26, who spoke Standard German and reported no history of speech or hearing problems. A 2 week perturbation experiment was conducted to assess motor equivalence in the production of / ʃ/. Two different types of artificial palates, an alveolar prosthesis and a central prosthesis, were used to perturb speech in this experiment. The alveolar prosthesis used the alveolar ridge as a landmark for potential adaptation and the central prosthesis had no landmarks, which provided less tactile feedback to the subject. Three of the subjects were recorded with an alveolar prosthesis and four with the central prosthesis. Sensors were placed on the tongue, upper lip, lower lip, and jaw. Each subject participated in 6 sessions with different conditions in each session. Nonsense words were spoken which targeted /s/ and / ʃ / in a carrier phrase. The second experiment evaluated the subject's auditory acuity, or ability to discriminate between different sounds. The speakers participated in a labeling test to determine their /s/-/ ʃ / boundary. Lastly, the speakers completed a discrimination test in order to assess their auditory acuity. *Results:* Analysis revealed that for individuals with lower auditory acuity there was a greater phonemic distance between /s/ and / ʃ /. Word duration was analyzed which demonstrated that slowed speech does not require much motor equivalence. Therefore, auditory acuity greatly influences the use of motor equivalence when word duration is taken into consideration. *Conclusion:* Speaker's use of motor equivalence strategies is contingent upon their own ability to perceive small differences in acoustic stimuli. Once the speaker is able to perceive the differences, then they will make corrections using motor equivalence. This finding may account for individual variations between participants in various research studies investigating motor equivalence. *Relevance to current work*: This study gave direction and information regarding motor equivalence and potential individual differences which were analyzed in the present study.

Brunner, J., & Hoole, P. (2012). Motor equivalent strategies in the production of German /ʃ/ under perturbation. *Journal of Speech Language and Hearing Research, 55*(4), 457-476. doi:10.1007/s00221-006-0848-1

Objective: This study explored the use of motor equivalent strategies when adapting to the perturbation of a palatal prosthesis. Three hypotheses were studied during this experiment. First, a positive correlation should exist between the horizontal position of the tongue tip and the lip position. Second, during the perturbation the speakers will position their tongue lower to prevent closure of the oral cavity. Third, adaption should not be possible while the auditory feedback is masked. *Method:* The participants in this study included two males and four females between the ages of 25 and 40 who all spoke Standard German. Each participant had orthodontic care for 1-3 years where they wore some sort of dental device. The study consisted of a two week perturbation experiment where each speakers' articulation was perturbed by a 1 cm palatal prosthesis, which they wore all day for the two weeks. The palates consisted of an alveolar prosthesis or a central prosthesis. Due to the individual speakers' prominence of their alveolar ridge, men received the alveolar prosthesis while women received the central prosthesis. An electromagnetic articulography recorded the speakers' articulatory movements. The sensors were placed on the tongue tip, back of tongue, middle of tongue, jaw and on each lip. The speakers were recorded throughout three different sessions with the stimuli being a carrier phrase then the nonsense word /shaxa/ which was spoken twenty times. Each session lasted approximately twenty minutes. The first time they were recorded with no perturbation. In the second session the speaker was recorded with the prosthesis in the oral cavity and their auditory feedback was masked with white noise. The third session included perturbation with auditory feedback without masking. The participants were also recorded after one week of wearing the prosthesis and after the second week with the prosthesis. Finally, all participants were recorded at the end without any perturbation. *Results:* The findings were consistent with the hypotheses stated above. As the tongue retracted more, the lips would protrude less. Two speakers demonstrated that when adapting to the perturbation they did not use motor equivalence. Adaption was found to not be impossible without auditory feedback. It was not possible at this time to determine whether or not changes between sessions two and three were due solely to lack or presence of auditory feedback. *Conclusion:* Speakers vary the position of their articulators in order to reduce the variability in their acoustic output. Speaker specific differences existed throughout this study as well as previous studies. It is known that some speakers adapt better than others. *Relevance to current work*: This study discusses the adaptation abilities of speakers after a perturbation is left in the vocal tract for a period of time. The findings from this work will guide the amount of perturbation in the present study and help anticipate effects it has on motor equivalence.

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 examined the contact patterns between the tongue and the palate when producing /s/ and /t/ with and without the presence of a bite block. *Method:* The participants consisted of three monolingual Arabic males and two native English speakers between the ages of 19-21. An acrylic bite block was placed between the molar and premolar teeth to increase vertical distances between the central incisors by 8-15 mm. This varying vertical distance between participants may have influenced the amount of compensation. Each subject participated in two sample sessions with a ten minute break between the sessions in order to adapt to the presence of the bite block. Each English participant produced the carrier phrase "say to me-again" and the Arabic participants produced the translated carrier phrase "you asked me – more" [saltlni-nkbar] with phonetically similar English (e.g., [saek],[baet] , [kes],[tes)]) and Arabic words (e.g., [saek], [baet], [kaes], [taeb]**)** randomly inserted. The participants produced lists of 20 sentences, at a constant rate and intensity level, four times. A pseudopalate and an acoustic recording device collected the data. The pseudopalate, made from a thin sheet of acrylic was molded onto a stone model of the hard palate, had 64 sensors that measured lingual-palatal contact. *Results:* The Arabic speakers demonstrated a narrower and more anterior /s/

than the native English speakers. The native English speakers showed a small change in speech production with bite block in place when producing /s/. The Arabic speakers produced /t/ more anteriorly than the English speakers. Two of the Arabic participants produced /t/ with the tongue contacting the first row of sensors. This suggests that the formation of the constriction for /t/ was made with the blade and the tip of the tongue while the English participants formed the /t/ with only the tongue tip. *Conclusion:* The Arabic participants showed the largest change between practice samples. The compensation for the bite block was not instantaneous for all participants. Some adapted quickly and produced speech that resembled normal speech patterns while others did not. The insertion of the bite block required more force and earlier contraction of the tongue raising muscles. Speakers did not compensate completely or instantaneously when producing /s/ and /t/ with a bite block. *Relevance to current work:* This study guided the adaptation time between sample sessions and the selection of stimuli. The current work took the measurements of the bite block into consideration when adjusting for individual differences in the size of the oral cavity opening.

Gentil, M. (1992). Variability of motor strategies. *Brain and Language, 42*(1), 30-37. doi:10.1121/1.2027904

Objective: This study explored articulatory control of the jaw and labial muscles as observed through electromyography. *Method:* Participants for this study included three American-English- Speaking individuals and three French-speaking individuals. The mandibular motor system and the labial motor system were analyzed in two separate studies. The mandibular motor system study involved the three American-English-Speaking individuals, ranging in age from 20-25. All participants reported normal dentition and no temporomandibular joint dysfunction. Wire electrodes were placed on seven mandibular elevator muscles (i.e., masseter superficial layer (SM), masseter deep layer (DM), medial pterygoid (MP), lateral pterygoid superior head (SLP), lateral pterygoid inferior (ILP), temporalis anterior (AT), and temporalis posterior (PT)) and one primary jaw opener (i.e., anterior belly of the digastric (ABD)). All electrodes were placed on one side of the subject. Jaw movements were then tracked with an overall accuracy within 0.1 mm using a magnetometer system. The speech stimuli consisted of three CVC syllables (i.e., tap, pap, kap) which were each repeated 15 times at two different speaking rates (i.e., fast and conversational). Each syllable was produced in the carrier phrase "It is …again." Each production was recorded and processed through a computer system. The labial motor system study involved three native French speakers with a mean age of 34. Wire electrodes were placed on seven labial muscles (i.e., orbicular oris inferior (OOI), mentalis (MTL), depressor labii inferior (DLI), orbicularis oris superior (OOS), depressor anguli oris (DAO), levator labii superior (LLS), buccinator (BUC)). Speech stimuli consisted of repeating /apa/ ten times at normal speaking rate. Each production was recorded and processed through a computer system as in the study above. *Results:* The mandibular motor system study revealed that individual variations were more common than a general universal pattern of use of mandibular muscles. The production of jaw movements differed among all three subjects. The labial motor system study revealed differences among each of the three participants in their lip movement. *Conclusion:* Even though individual differences were observed with muscle activation among the participants, speech goals were always achieved. Differences may be due to size, shape and form of the maxilla and the mandible of each participant. The study concluded that the same speech motor action can be obtained many different ways, which leads to knowledge that the nervous system is flexible in regards to producing articulatory movements. *Relevance to current work*: Participants demonstrated the use of motor equivalence with labial and mandibular muscles, which is a focus of the current work.

Guenther, F. H., Espy-Wilson, C. Y., Boyce, S. E., Matthies, M. L., Zandipour, M., & Perkell, J. S. (1999). Articulatory tradeoffs reduce acoustic variability during American English /r/ production. *Journal of the Acoustical Society of America, 105*(5), 2854-2865. doi: 10.1121/1.426900

Objective: This study explored the articulatory variations in /r/ production in different contexts and the trading relationship between articulators in order to achieve an accurate /r/. *Method:* There were seven participants with no history of speech, hearing or language deficits. Transducer coils were attached in the midsagittal plane to the lips, tongue and lower incisor. Three coils were attached to the tongue, two coils to the lips and one to the lower incisor. Each participant repeated the carrier phrase “Say _____ for me” 4- 7 times for each of the five words (i.e., /warav/, /wabrav/, wadrav/, /wagrav/, and /wavrav/.) *Results*: Many different tongue shapes were seen within and across subjects. Analysis of the lingual movements showed that three subjects utilized different articulatory gestures to produce /r/. Subject 1 produced /r/ in /wadrav/ by moving the tongue back with a slight downward movement of the tongue blade which was different than the /r/ production by the same participant when producing the /r/ in /warav/, /warav/ and /wabrav/. The tongue shape while producing /wagrav/ were much closer to the shape of the tongue for /g/ than the /r/ shape for /warav/ or /wabrav/. Each participant demonstrated a trading relationship between the tongue back height and the front horizontal position of the tongue. *Conclusion:* This study showed a large variation of tongue shapes when producing /r/ in different phonetic contexts. Each participant demonstrated /r/ slightly differently depending on the phonetic context. Coarticulatory effects on /r/ production determined tongue placement and movement. *Relevance to current work*: The current work explored the movement and shape of the tongue when producing /r/. The findings from this study were used to lead the researchers in stimuli creation and tongue movement analysis.

Hughes, O. M., & Abbs, J. H. (1976). Labial-mandibular coordination in the production of speech: Implications for the operation of motor equivalence. *Journal of Phonetics, 33*(3), 199-221. doi:10.1159/000259722

Objective: The study explored speech movement coordination between the upper lip, lower lip and jaw. *Method:* Participants for this study included six native English-speaking women. Productions of three different vowels in a phrase containing di-syllable words were analyzed at two speaking rates in order to measure the displacement of each articulator. *Results:* Data analysis revealed evidence of motor equivalence in the articulator movements that contributed to the achievement of speech goals. Vertical opening of the mouth demonstrated little variation; however, the lower lip and jaw displacement changed greatly while producing the same target. Dependence was observed between lower lip and jaw movements, but was not seen with the upper lip. The upper lip contributed to only 1% of the vertical mouth closure which left the lower lip and jaw to contribute 99% of vertical closure. Even though the upper lip did not appear to contribute as much as the lower lip, the upper lip demonstrated compensatory capabilities for overall lip closure when the lower lip had reduced displacement. Different speaking rates led to few changes in the displacement of the articulators. *Conclusion:* The data revealed motor equivalence during speech production, with varying levels of motor equivalence among speakers. *Relevance to current work*: This is a seminal paper in the area of motor equivalence and serves as a primary motivator for the present study.

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. Experiment 1 was carried out in order to explore this idea further. The subject 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 3 was carried out to combine the finding of the first two experiments by examining the reactions of the jaw perturbation. 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 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 5.88 N 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 which was found by measuring the jaw height at the first acoustic evidence of lip closure. 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 found, also, 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/ which was hypothesized. Structure coordination is required for speech production as found in this experiment as well as static perturbation experiments. The adaptive reactions observe 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 current work:* The current work examined the effect of static perturbation to speech production. This study gave insight into dynamic perturbation and the finding therein.

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*(1), 14-21. doi:10.2319/032911-226.1

Objective: The aim of this study was to analyze the effects of the Hawley retainer on speech sounds. *Method:* The participants in this study were 12 adolescents, three males and 9 females, who were between the ages of 11.11 and 18.03. They were all monolingual native Turkish speakers with no articulation disorders. Each patient was instructed to wear the retainer 24 hours a day for 6 months. The only time they were to remove the retainer was while brushing their teeth. The Hawley retainer is a removable retainer that fits against the lingual surface of the teeth and palate. This retainer acted as a perturbation in this study as it affected speech articulation. The speech sounds were assessed based on objective acoustic evaluations of vowels and subjective articulation assessment of consonants. The participants were evaluated on the first day, one week later, four weeks later and three months later. Each participant's articulation abilities were evaluated twice on day one. Once prior to the initiation of wearing the retainer and once with the retainer in place. During the articulation assessment, each participant was analyzed by a speech-language pathologist and each unintelligible or distorted syllable was marked accordingly. The acoustic evaluation measured formant frequencies using a computer program. Participants were given a practice trial for each task following the model by the clinician. The tasks included productions of the vowels [æ, e, a, u] at comfortable pitch and loudness levels. *Results:* The articulation assessment revealed statistically significant distortions with /s/ and /z/ consonants. During the initial evaluation on day one, six of the twelve participants demonstrated distorted /s/. At the one week evaluation seven participants demonstrated distorted /s/. At the fourth week evaluation, four participants demonstrated distorted /s/ and at the third month evaluation, only three patients presented with a distorted /s/. For the distorted /z/, six participants presented with it on the first day, at the one week only two presented with it and it disappeared on the fourth week and third month evaluations. The acoustic analysis results demonstrated no statistically significant difference in formant frequencies for /ɑ/, /e/ or /u/. The production of /i/ did have a significant difference in its formant frequencies. *Conclusion:* Oral appliances can cause differences in speech production due to possible tongue posture or palatal volume changes. These appliances alter the shape and length of the vocal tract which then change vowel quality and resonance frequencies. Articulation of high front vowels was distorted due to changes in the anterior portion of the oral cavity. Participants wearing the Hawley retainer can adapt their articulatory patterns around the retainer, but adaptation can take anywhere from one week to three months. *Relevance to current work*: A perturbation at the anterior portion of the oral cavity causes certain changes in speech production. These findings helped guide the use of perturbation in the current study

Lee, J., Shaiman, S., Weismer, G. (2016). Relationship between tongue positions and formant frequencies in female speakers. *Journal of the Acoustical Society of America, 139*(1), 426-440. doi: 10.1121/1.4939894

Objective: This study examined the realtionship between tongue kinematics and acoustic vowel space for the four corner vowels (i.e., ɑ, æ, i, u). *Method:* The participants for this study consisted of thirteen female adults. Acoustic recordings and electromagnetic articulography was used to gather tongue movement and acoustic data during ten speech task where the vowels were inserted into CVC words (i.e., hVd, dVd). Three sensors were attached to each participant's tongue (i.e., tongue tip, tongue body, tongue dorsum). A reference sensor was attached to the gingiva between the upper incisor. Each participants read the Rainbow Passage for three minutes before recordings began in order to get used to the sensors. Kinematic data was gathered at 200 Hz. Data was gathered across five different conditions (i.e., habitual, fast, loud, slow, soft). *Results:* Significant differences occurred during the different CVC words for both acoustic and kinematic vowel spaces. These differences changed the x-y tongue positions which indicated an effect for all vowels. The vowels /ɑ/ and /æ/ were less low in the vowel spaces for dVd compared to hVd. The vowel /i/ was less forward in the dVd utterance and the vowel /u/ was more forward for the dVd utterance compared the the hVd utterance. Formant frequencies and tongue positions showed significant covariation between acoustic data and tongue movement for the tongue body sensor. *Conclusion:* Correlations between acoustic data and kinematic vowel spaces were weaker between speakers. Tongue height variations account largely for variations seen in F1. Tongue position correlations to F2 were less clear within this data set. *Relevance to current work:* The current study used electromagentic articulography in order to gather articulator kinematic data. This study had vowels results which were slightly comparative to the current work.

McFarland, D. H., & Baum, S. R. (1995). Incomplete compensation to articulatory perturbation. *The Journal of the Acoustical Society of America, 97*(3), 1865-1873. doi:10.1121/1.412060

Objective: This study explored individual speech adaptations as a result of articulatory perturbation. *Method:* The participants included 15 native French speaking women aged 20-33 with no speech or language disorders. They also presented with typical mouth closure. Two subtests, the immediate compensation subtest and the postconversation subtest, were administered to each participant. The immediate compensation subtest consisted of three conditions: normal, small bite block (SBB; 5 mm for CV and 2.5 mm for vowels), and large bite block (LBB; 10 mm for CV and 22.5 mm for vowels). The postconversation subtest consisted of two conditions: normal and single bite block (10 mm). *Results:* The immediate compensation subtest and postconversation subtest results were analyzed based on duration 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 and normal conditions. Duration of / ʃ / during the SBB condition were substantially longer than in the other conditions. Within the postconversation subtest, little influence was demonstrated by the bite block on duration. The spectral measures of the immediate compensation subtest demonstrated higher F1 frequencies in the LBB condition than the SBB or normal conditions. F2 demonstrated similar findings to F1. Seven of the subjects produced /t/ with centroids lower in the LBB condition while the fricatives demonstrated higher centroid frequencies in the normal condition compared to the other bite block conditions. Postconversation subtest demonstrated no 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. *Conclusion:* The present study revealed that speech adaptation due to the presence of a bite block was not consistent with previous research that suggested immediate compensation to perturbation. It also revealed greater effects on consonants due to the perturbation than vowels. Individual differences in the area of compensatory strategies were not consistent. *Relevance to current work*: The present study includes articulatory perturbation with the use of bite blocks. These findings helped guide the use of bite blocks and determine which analyses were used in the current study.

Mohsenin, Vahid (2003). Effects of gender on upper airway collapsibility and severity of obstructive sleep apnea. *Sleep Medicine*, *4*(2003) 523-529. doi: 10.1016/S1389-9457(03)00168-0

Relevance to the current work: this study provided evidence regarding gender differences in the size of the participants' vocal tracts, as well as articulators.

Nieto-Castanon, A., Guenther, F. H., Perkell, J. S., & Curtin, H. D. (2005). A modeling investigation of articulatory variability and acoustic stability during American English /r/ production. *Journal of the Acoustical Society of America, 117*(5), 3196-3212. doi: 10.1121/1.1893271

Objective: This study examined the relationship between the variability and stability of acoustic cues during /r/ production. The effects of articulatory movement on the acoustic variable F3 were observed. *Method:* Seven participants produced /r/ in five different phonetic contexts (e.g., "warav," "wabrav," "wavrav," "wagrav," "wadrav") while transducer coils tracked the movement of the tongue, jaw and lips. Each participant repeated each production two to five times while being recorded by a directional microphone. *Results:* The acoustic variable F3 provided the best prediction of the variability in the production of /r/. Deviation from an average /r/ configuration resulted in low F3 stability and small articulatory variability. An average of 91% of the articulatory variability showed a small effect on F3. An average of 9% of the articulatory variability demonstrated a large impact on F3. *Conclusion:* Analysis of /r/ in different phonetic contexts revealed a strong relationship between the acoustic stability and articulatory variability. This led to the notion that many different articulatory configurations can be used in order for a listener to identify the phoneme. The amount of articulatory variability can be predicted by the level of F3. Deviation from an average /r/ production resulted in low F3 stability. *Relevance to current work:* The current study observed the production of /r/ while adapting to a perturbation. Results from this study were used in determining /r/ contexts and the effects on F3.

Paley, J. S., Cisneros, G. J., Nicolay, O. F., & LeBlanc, E. M. (2016). Effects of fixed labial orthodontic appliances on speech sound production. *Angle Orthodontist, 86*(3), 462-467. doi:10.2319/052415-351.1

Objective: The purpose of this study was to explore fixed labial orthodontic appliances and their impact on speech sound productions. *Method:* The participants of this study included six males and 17 females whose age ranged from 11-24;11 with three different types of malocclusions (i.e., angle class I, class II and Class III). Each participant needed fixed labial therapy. The fixed appliances were metal brackets with similar dimensions across all participants. Speech samples were gathered over the course of ten weeks. Sample 1 was gathered immediately prior to appliance insertion. Sample 2 was gathered immediately following appliance insertion. Sample 3 was gathered 4-5 weeks post insertion of the appliance. The final sample was gathered 8-10 weeks post insertion of the appliance. Speech samples were gathered in a noise-reduced environment. A video camera recorded all speech samples with an omni-directional microphone positioned at the participants shoulder height and two inches below chin level. The assessments were performed by two speech pathologists and one speech physiologist. An experimenter stood behind the participant and stated the desired utterance or sound and the participant would then repeat it. The specific target sounds for this study were /t/, /p/, /f/, /s/, /sh/, /ch/, /dz/, /k/, /th/, /l/ and /m/. Analyses were performed in the perceptual, visual and physiologic areas of each production of the target sounds at the isolation, syllable, word, phrase, conversational, and counting levels. Placement, manner and type of error were analyzed. *Results:* Sound production errors were present in four participants at baseline. At the final sample, 13/23 (56%) participants demonstrated new sound errors with the remaining 10 (44%) never demonstrating sound errors. Out of the eleven speech sounds examined, only six speech sounds results in sound errors (i.e., /ch/, /dz/, /sh/, /f/, /s/, and /t/). The /s/ and /sh/ were the most commonly affected. Analyses of the articulatory movements showed that 11/23 (85%) of the participants presented with anterior tongue movements (fronting) during speech production, while one participant presented with a retracted position of the mandible. One participant presented with variable changes across multiple sounds. *Conclusion:* The insertion of the fixed labial appliances had a negative impact on speech production in 57% of the participants with 31% of the affected participant's continuing to demonstrate sound errors after two months. The findings from this study were consistent with the findings from other studies which found that /s/ and /t/ were the most frequent error sounds. The four participants who showed new sound errors during the later months of evaluation were evaluated again after 6-8 months and all demonstrated complete resolution of errors. Some individuals adapted to the presence of the appliance more quickly than other participants. *Relevance to current work*: In the current study, a bite block will be used to perturb the production of speech sounds. This study demonstrated which speech sounds are distorted most frequently when a labial fixed appliance is placed in the mouth.

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*(5), 2948-2961. doi: 10.1121/1.405814

Objective: The author of this study hypothesized that the speech motor programming goal is acoustic in nature, and this was explored by examining two independent articulatory parameters. For the production of the vowel /u/, kinematic measures were made of both tongue raising and lip rounding. When the tongue body is less raised, the lips are more rounded or vice versa. *Method:* The participants in this study were four male speakers of American English. Each demonstrated several mm of lip protrusion while producing /u/. The stimuli included ten different utterance types with a total of 300 different utterances spoken by each participant. The utterance materials were written on a sheet of paper placed in front of the participant. The transducers were placed on the upper lip, lower lip, the gingival papilla between the two central incisors, the tongue body, bridge of the nose and upper incisors. Dental casts of each participant's hard palates were used to quantify the relationship between area function and articulatory data. *Results:* No significant positive correlations were found between rounding of lips or tongue movement. The production of /u/, which is produced by the contractions of the styloglossus, the posterior genioglossus and the inferior longitudinal muscles, was produced by all four subjects with a larger opening in the oral cavity. The finding of negative correlation between lip rounding and tongue raising provided support for the motor equivalence hypothesis. Participant 1 showed a different pattern than the others which may demonstrate individual differences. *Conclusion:* The results from this study demonstrate the idea that if motor equivalence presents itself in these ways, then there could possibly be a number of compensatory or different ways a certain person produces a particular sound. *Relevance to current work*: The current work considered the results of this study to increase our understanding of motor equivalence. The placement of the transducers was also taken into consideration in the current work.

Stevens, K., Bressmann, T., Gong, S. G., & Tompson, B. D. (2011). Impact of a rapid palatal expander on speech articulation. *American Journal of Orthodontics and Dentofacial Orthopedics, 140*(2), e67-75. doi:10.1016/j.ajodo.2011.02.017

Objective: The study examined patients who wore a hyrax rapid palatal expander (RPE) and the typical patterns of speech adaptation. *Method:* The participants for this study consisted of thirteen females and nine males ranging from 9-19 years of age. The need for the palatal expander was determined by their treating orthodontist. These palatal expander are used to widen the maxillary arch. Each participant decided which palatal expander they preferred, either the banded expander or the bonded expander. The banded expander is fixed with dental bands to the first premolars and first molars. The banded expander demonstrated similar effects of a small bite block. The bonded expander has acrylic attachments that cover the lingual, buccal and occlusal surfaces of the premolars and molars. A speech sample was gathered six times throughout the treatment process which was approximately five minutes in length. The speech stimuli consisted of fifteen sentences from the sentence module of the Fisher-Logemann test of articulation and twenty sentences from the Great Ormond Street speech assessment. The six recordings took place right before RPE placement; 15 minutes after placement; 2-4 weeks after first recording; 2-3 months after first recording; after the RPE was removed, 5-6 months after first recording; and 1-2 months after the RPE was removed, about 6-8 months after the first recording. Acceptability ratings were calculated for each recording which determined acoustic data and data distributions. *Results:* The ratings by each listener demonstrated that at the participant's speech acceptability scores increased. Each participant's scores increased as their speech production improved over time. By the last speech sample session, each participant's speech acceptability rating had improved. No significant difference was found between the bonded and the banded appliance types. *Conclusion:* RPE had a negative effect on the patient's speech production according to listener speech acceptability ratings. The bonded appliance did not cause any additional speech distortions compared to the banded appliance, even though the bonded appliance had the bite-block effect. Compared to other studies, the RPE is more intrusive and limits the tongue's movements more than a bite block. *Relevance to current work*: The RPE perturbed each participant's speech in significant ways, especially at the beginning. The current work uses a different type of perturbation, but also measures adaptation time.

Tiede, M., Boyce, S., & Epsy-Wilson, C. (2007). Variability of North American English /r/ production in response to palatal perturbation. Haskins Internal Workshop on Speech Production and Motor Control, *Massachusetts Institute of Technology,* Acoustics of Vocal Tract Shapes for Liquids, NIH DC05250

Objective: This study explored the different articulatory strategies an individual uses when producing /r/ and how different articulatory strategies create acoustic differences. *Method:* The participants were one male and two females who were native English speakers. Each participant had a custom palatal prosthesis placed in their mouth. The palatal prosthesis was 6 mm at the alveolar ridge and tapered to 1 mm. The participants produced /ara/, /iri/, and /uru/ in isolation 10 times per condition. The conditions consisted of Block 1 (pre-perturbation); Block 2 (immediately following prosthesis Insertion); Block 3 (post-adaptation prosthesis still in place) and Block 4 (immediately following prosthesis removal). Each production was audio recorded and EMA recorded. Transducers placed on the upper lip, lower lip, lower incisor, upper incisor, tongue tip, tongue blade and back of the tongue were used to track the articulatory movements. F3 minimum was evaluated before and following a vowel. *Results:* Each participant demonstrated distinct pre-perturbation postural preferences and produced both bunched and retroflexed postures. In response to the perturbation the tongue tip angle was decreased. The participants demonstrated a preference for a bunched tongue when producing /iri/. The perturbation affected the male participant the least. The perturbation affected the first female the most as she changed her preferred bunched posture to retroflex for the production or /uru/. The second female adapted the most to the perturbation, but showed the greatest difference from original tongue position. The participants showed effects of perturbation on F3 and preserved vowel identity during /r/ production. *Conclusion*: The same sized palatal prosthesis was used for each participant. The perturbation affected the larger male vocal tract the least. The participants demonstrated more than one strategy for /r/ production and each strategy produced a formant structure of an /r/. *Relevance to current work*: A bite block was used in the current work to perturb /r/ production. Results gathered from this study were used to guide the placement of transducer coils and indicate possible effects of perturbation to /r/ production.

Westbury, J.R., Hashi, M., & Lindstrom, M. (1998). Differences among speakers in lingual articulation for American English /r/. *Speech Communication, 26*(3), 203-226 doi: 10.1016/S0167-6393(98)00058-2

Objective: This study explored inter-speaker variation in tongue shape for /r/ production and how tongue shapes may vary depending on phonetic contexts. *Method:* The participants for this study consisted of 57 typical young adult speakers between the ages of 18 and 30. In order to collect kinematic data, each speaker had a set of small pellets (i.e., golds beads 3 mm in diameter) placed mid-sagittally on the tongue (i.e., tongue blade, dorsum, and two intermediate locations). Each participant produced five test words (i.e., *row, across, problem, street* and *right*) in isolation five times. The measurement of the oral cavity shape and size came from stone models of each participant's maxillary arch and palatal vault. *Results:* When producing /r/, many of the participants created a bunched tongue shape while others were noticeably retroflexed. However, some participants produced tongue shapes that were not matched to either of these descriptive labels. The least variable tongue shapes for /r/ appeared in the word *street*. The participants demonstrated increased variability when producing the words *row, right,* and *problem.* When the participants produced the words *across* and *row*, a greater bunching of the tongue was observed. The speakers, whose tongue pattern did not reflect a bunched or a retroflexed shape, produced /r/ in *problem* with the tongue shifted down and to the left. Formant frequencies for /r/ in *row* and *right* appeared lower than expected. The differences in tongue shape were not accompanied by differences in formant frequencies. *Conclusion:* The generally accepted classes of tongue shapes for /r/ (e.g., retroflexed or bunched) may be more convenient than real. Many of the participants only inconsistently used these configurations when producing /r/. The tongue shapes for /r/ changed depending on the phonetic context. Similar shape and movement of the tongue appeared when /r/ was produced in the initial position followed by a back vowel. Formations of different tongue shapes and movements appeared in /r/ clusters (e.g., *street*). *Relevance to current work:* The current work examined the production of /r/ and used the information from this study to guide the placement of transducer coils and the selection of possible stimuli.

Westbury, J.R., Lindstrom, M., & McClean, M. (2002). Tongues and lips without jaws: A comparison of methods for decoupling speech movements. *Journal of Speech Language and Hearing Research*, *45*(1), 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:* The participants from this study consisted of 44 normal young adult speakers of American English. Markers were placed on the tongue, lips and jaws to track the articulatory movements. Each speaker 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. *Conclusion:* 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.

Westbury, J.R., Severson, E.J., & Lindstrom, M. (2000). Kinematic event patterns in speech: special problems. *Language and Speech*, *43*(4), 403-428. doi: 10.1177/15441130301400604

Objective: This study explored coordination patterns among speech articulators. *Methods:* Kinematic data was gathered using XRMB-SPD small gold pellets which were glued to the tongue (i.e., tongue tip, tongue body, tongue dorsum), the vermillion border of each lip and the incisors. The sensors tracked the x and y coordinates of the tongue and lip movements. Each participants said the test words *special* and *problem* five times. This study specifically examined the initial VC transition. *Results:* Average durations of the VC production were analyzed. The results showed faster and earlier movement of the lower lip into the /b/ of *problem* than the initial vowel movement in *special*. *Discussion:* The lips and jaw moved increasingly fast for both vowel movements. The sequencing of the tongue and jaw movements differed across participants. *Relevance to current work:* The current work used similar placement of the sensors on the tongue and lips, as well as exploration of vowel qualities.

Zhou, X., Espy-Wilson, C. Y., Boyce, S., Tiede, M., Holland, C., & Choe, A. (2008). A magnetic resonance imaging-based articulatory and acoustic study of "retroflex" and "bunched" American English /r/. *Journal of the Acoustical Society of America, 123*(6), 4466-4481. doi:10.1121/1.2902168

Objective: The study examined the differences between F4 and F5 when speakers produced /r/. *Method:* Two males between the ages of 48 and 51 with similar F1-F3 values who produced very different bunched and retroflexed tongue shapes when producing /r/ participated in this study. Both participants had similar palate lengths, palate volumes, vocal tract lengths and overall stature. Articulatory data gathered for each participant included MRI scans of the vocal tract, dental cast measurement, computed tomography and acoustic recordings. Participants, positioned in the supine posture, produced a sustained /r/ as in "pour" for 5-25 seconds during the MRI scans. Throughout the MRI scan, an acoustic recording was gathered in order to measure F1-F5. Each participant was also acoustically recorded in a separate session where they produced a set of utterances which included sustained productions of /r/ and real and nonsense words containing /r/. The real words included words with /r/ in the initial, final and intervocalic positions. The nonsense words consisted of *wadrav, warav, wavrav*, and *wagrav*, which were all repeated with stress either on the first syllable or on the second syllable.

Additionally, participants sustained /r/ as in *reed, right,* and *role.* Each acoustic recording was gathered in such a way so that F1-F5 could be measure reliably. *Results:* Acoustic samples gathered in the MRI showed that each participant produced characteristic F4/F5 patterns. F4/F5 patterns showed differences when the participants produced /r/ in the upright position. The distance between F4 and F5 increased for the retroflexed /r/. The distance between F4 and F5 was 1469 Hz for the retroflexed /r/ and 651 Hz for the bunched /r/. *Conclusion:* The frequency spacing between F4 and F5 appeared different depending on whether there was a bunched tongue shape or a retroflexed tongue shape. The results showed that F4 and F5 spacing were reliable indicators of tongue shape, at least for either a retroflexed or a bunched tongue shape. *Relevance to current work:* The current study analyzed the movements of the tongue and the frequency of the formants when adapting to a perturbation. These results found in this study influenced the gathering of data and analysis.

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

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.

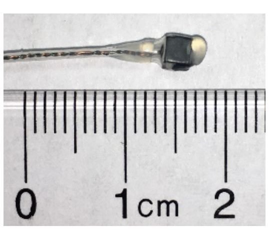
Participation
Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without jeopardy to your class status, grade, or standing with the university.

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:



tracking sensor

bite block

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