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# Kinematic and Acoustic Vowel Changes in Adult Bite Block Speech

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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The current study examined the lingual kinematic and acoustic effects of bite blocks on vowels in a sentence context. Twenty adult native English speakers (10 male, 10 female) with no speech, language, or hearing deficits participated in the study. The corner vowels found in the sentence, *The blue spot is on the black key again* (i.e., /u/, /ɑ/, /æ/, /i/), were measured kinematically and acoustically immediately before and after bite block insertion. The participants' speech was audio-recorded and their lingual articulatory movements were measured with a Northern Digital Instruments Wave electromagnetic articulograph. The sensor coils were attached to three different parts on the tongue (back, middle, and front). Acoustic analysis of the vowel formants revealed that the vowel articulation index and vowel space area decreased significantly following bite block insertion. Kinematic analysis of the sensors on the tongue revealed that the kinematic vowel articulation index decreased significantly for the back and middle of the tongue but not for the front. Thus, adjustments to the position of the front of the tongue were sufficient to compensate for the bite block perturbation, while the same measures for the back and middle of the tongue were significantly affected. This was likely due to the relative independence in the movement of the front of the tongue, given its distance from the posterior point of attachment between the tongue and mandible. These findings suggest that the effects of articulatory perturbation can be more fully understood when kinematic and acoustic measures are considered together.

Keywords: kinematics, acoustics, bite block, perturbation, compensation, vowels

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# DESCRIPTION OF THESIS STRUCTURE

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

# Introduction

From early infancy humans experiment with articulatory movements to shape, direct, or impede air flow to create different sounds. Factors like tongue height, tongue advancement, and lip rounding soon become familiar adjustments while children learn to articulate in a natural way through trial and error. This trial and error process results in consonants and vowels that become familiar articulations in their language.

## Levels of Speech Measurement

Perception of speech is used every day during conversation; we use this to subconsciously interpret speech sounds and understand what speakers are saying in a natural and straightforward way as we hear words. We rely on this perception to judge the quality of speech, which includes a standard of accuracy for both consonants and vowels. The present work will focus on vowels specifically. Perceptual analysis for vowel accuracy in an experimental setting uses this recognition in a more conscious way, with listeners relying on their own perceptions to form judgments of speech sounds rather than depending on instrumentation to provide objective measures (Kent, 1996).

Perceptual measures are also the least precise way of assessing vowels (Kent, 1996). Generally, vowel production can include a fairly wide range of acceptable sounds and even speech that is disrupted by something foreign in the mouth—for example, a bite block—can be adequately perceived and understood correctly (Jacks, 2008). This is not to say that perceptual measures are less valid in a vowel study; everyday conversation relies on the human ear without the need for technology. Many studies use a perceptual measure because the researchers are interested in the generalization of research to typical communication (Jacks, 2008; Stevens, Bressmann, Gong, & Tompson, 2011). But perceptual measures are subject to human biases;

dialect and diverse language experiences can influence how acceptable a vowel may be to a given individual. This kind of subjectivity is useful in drawing conclusions about speech naturalness but limits the precision needed in the present work to describe more explicitly how vowel production is influenced by the presence of a bite block. This study will extend the findings from previous perceptual studies by using instrumental measures of speech production.

Vowels have unique characteristics acoustically. They are composed of multiple harmonic frequencies produced by the larynx which are filtered by the vocal tract. The frequencies selectively resonated by particular portions of the vocal tract represent concentrations of acoustic energy known as formants (Behrman, 2018). The formants of the vowels can be displayed on spectrograms, allowing them to be distinguished from other sounds. Typically, speech scientists identify a vocalic sound from the frequencies of the first two formants (Behrman, 2018; Lee, Shaiman, & Weismer, 2016). The frequency of the first formant is inversely related to the tongue height of the speaker when producing the vowel and the second formant is directly related to tongue advancement. Acoustic analysis is an example of an instrumental approach that can quantify vowel production in a way that complements what perceptual assessment can tell us. Acoustic measures are advantageous because the recording process does not have any effect on the speech production due to its noninvasive nature—it can be recorded at any time in any place. However, acoustic measures can only reflect general changes in vocal tract configuration. The position or specific movement trajectory of an articulator is not detectible from acoustic analysis alone.

Another instrumental method of speech analysis—kinematics—directly quantifies articulator movements during speech production. In kinematic studies sensors are adhered to the articulator surfaces so that the movements of the articulators can be tracked and the trajectories of the tongue, jaw, and lips can be recorded in real time as speech sounds are articulated (Namasivayam, van Lieshout, & De Nil, 2008). This kind of measurement can give us information about the movements of the articulators in ways that perceptual and acoustic analysis cannot. But this kind of measurement is not without its disadvantages.

Just as acoustic and perceptual measurements are simple to obtain with relatively little instrumentation, successful kinematic studies involve the use of technologies that can be quite invasive (Namasivayam et al., 2008). The presence of sensors, wires, and glue within and around the oral cavity can cause interference in the speech patterns and the process of adhering the sensors is time-consuming and invasive. Some of the potential disturbances caused by the presence of the sensors have been reported in previous kinematic studies (Dromey, Hunter & Nissen, 2018). Knowing how the tongue, jaw, and lips coordinate to produce vowels when patterns of articulation may differ between speakers is why kinematic analysis matters. This study used both kinematic and acoustic analysis to examine vowels and how the articulation changes when a variable is manipulated—namely, by perturbing vowel production by placing bite blocks between the molars in order to remove the typical contribution of the mandible.

**Perturbation and Adaptation**

Perturbation is used in studies to assess adaptation to oral obstacles (like bite blocks) by intentionally disturbing speech production (Namasivayam et al., 2008). In this way, deliberate perturbation can result in understanding about how the brain adapts to such obstacles. These findings can be generalized to rehabilitation of speech disorders that perturb speech. For example, physical changes to the articulators (e.g., missing teeth, glossectomy) could structurally inhibit typical speech production. Dysarthria can also affect the vocal tract's ability to move appropriately and resonate properly. Perturbation studies can teach us about human adaptability and the articulatory movements that are required to achieve an acceptable speech outcome despite perturbed movement patterns.

For most speakers, the articulatory adaptation needed to compensate for vocal tract perturbation is not especially difficult to achieve; normal sensory feedback allows the brain to flexibly adjust the movement of the articulators when necessary (McFarland & Baum, 1995). Once someone experiences articulatory perturbation, their tendency is to adapt in order to articulate the message as clearly as possible. But what does this compensation look like and how does it vary across speakers once their speech is perturbed?

Articulatory change, when adapting to perturbation, has been documented in several studies (Campbell, 1999; Gay, Lindblom, & Lubker, 1981; Namasivayam et al., 2008). An orthodontic retainer is a common example of a perturbation that may be experienced in everyday life. In the perturbation study of Kulak Kayikci, Akan, Ciger, and Ozkan (2012), most of the participants who were recorded during an articulation test did not demonstrate statistically significant speech disturbances in the vowels /e, a, u/ but many demonstrated those disturbances on the vowel /i/. The time taken to fully adapt to the perturbation caused by the retainer also varied across speakers, but overall /i/ in particular proved difficult to compensate for under perturbed conditions. Similarly, McFarland and Baum's (1995) study analyzing speaker adaptation to more contrived perturbing appliances (i.e., bite blocks) reported individual differences in compensation ability. The time required for the participants to fully adapt to the perturbation varied across the speakers, but McFarland and Baum concluded overall that adaptation to vowel perturbation appeared easier compared to adaptation to consonant perturbation because we tend to have a lower tolerance for consonant error compared to vowels.

These acoustic differences in perturbed speech could be further understood if supplemented with kinematic measurement.

Jacks (2008) explored how speech perceptually changes when perturbed with a bite block in both typical speakers and those with acquired apraxia of speech. The researchers initially recorded the “idealized” versions of three vowels (i.e., /ɪ, æ, ɛ/) in isolated, one, two, and three-word contexts. They then compared these recordings with the same stimuli produced by the participants after bite blocks were inserted between their molars. The results indicated that all speakers had incomplete compensation to the bite block constraints and the vowel production of each participant was impaired perceptually. The researchers concluded that the bite block contributed to a decrease in perceived accuracy for all of the speakers. However, because both the healthy controls and speakers with apraxia showed a decrease in accuracy of a relatively similar magnitude, the researchers could only draw general conclusions about their initial hypothesis (i.e., whether neural feedback control systems are intact in speakers with apraxia of speech) from the perceptual data.

Acoustic changes to vowels under perturbed conditions were also explored by DeJarnette (1988) to investigate compensatory articulation. DeJarnette measured the first two formants of the isolated vowels /i, æ, a, u/ in both unconstrained and bite block conditions in 15 participants. Though the results indicated that the formants from each vowel production were within normal ranges, the author drew the following conclusion: the first formant was affected significantly by the presence of the bite blocks for /a/ when none of the other vowels were affected in the same way. She concluded overall that speech-motor compensation for perturbation is likely context-dependent and that perhaps individual vowels would not vary too much from unconstrained vowels in the typical formant range. The results appeared unremarkable for most of the vowels produced, but investigation of the compensatory articulation could have been more thorough with kinematic data, since acoustically, the perturbed vowels were within normal formant ranges. These studies demonstrate variation across speakers, but since all the data presented in these studies only documented the differences in articulation acoustically and perceptually, the present study used kinematic data to show how the articulator movements changed in order to compensate for perturbation. The exact trajectory of the tongue, lips, and jaw in vowel production is unknown in most perturbation studies and that is why kinematic measures alongside acoustic analysis are important.

**Motor Equivalence**

The differences in how speakers constrict their vocal tract to achieve the same phonemic output is known as motor equivalence. By using several articulators in different combinations, the vocal tract shape changes, but the end result is a similar perceptual and acoustic output (Brunner & Hoole, 2012). The vocal tract configuration can differ based on the relative contributions of upper and lower lip coordination, tongue placement and velopharyngeal constriction during speech. However, due to motor equivalence, the exact way in which the speaker's articulators adapt to compensate for perturbation is hidden when only measured perceptually and acoustically.

The articulatory trade-off for the high back corner vowel /u/ is a prime example of how motor equivalence is at work while resulting in similar acoustics. It has been long recognized that the vowel /u/ is not only a product of tongue positioning, but that it is also fundamentally shaped by the rounding of the lips (Perkell, Matthies, Svirsky, & Jordan, 1993). This creates a trading relationship between posterior tongue height and lip rounding. A speaker can compensate for less posterior tongue height by rounding the lips more; and conversely, more tongue height requires less rounding of the lips. Acoustically, the precise contribution of lip rounding is not detectable. Kinematically, the tongue height and lip rounding can be measured to determine the relative contribution of each.

Since most perturbation studies having to do with vowels have only discussed vowel naturalness and acceptability through perceptual and acoustic patterns, the realm of investigating how the body's articulatory mechanics adjust in the production of vowel sounds is relatively unexplored. Perceptually, speakers will attempt to maintain vowel identity through articulatory adjustments when their speech is perturbed because they want to communicate as clearly as possible. The speaker therefore will attempt to shape the vocal tract in whatever way is needed to articulate the sounds clearly.

**Aims of the Study**

The articulatory changes that result from speakers' attempts to correctly produce vowel sounds in spite of perturbation is the focus of the present study. The study aims to measure this change acoustically by analyzing the formant frequency changes, as well as kinematically by analyzing the trajectories of the articulators with kinematic sensors. The goal is to build upon the foundations laid by previous acoustic and perceptual studies having to do with vowel perturbation and to complement those measures with kinematic analysis, revealing the movements that underlie modified speech. It was hypothesized that there would be articulatory differences between the participants as a result of motor equivalence as each attempts to compensate for the bite block in his or her mouth.

# Method

## Participants

Twenty native English-speaking adults with no history of speech, language, or hearing disorders participated in the study. The mean age was 23.9 years (*SD* 1.3) for the 10 women and 25.0 (*SD* 1.9) for the 10 men. These individuals 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.

## Instrumentation

Each participant was seated in a single-walled sound booth 30 cm from a condenser microphone (AKG C2000B) during recordings. A calibration tone was recorded in the microphone channel to allow for measurement of speech intensity in dB SPL at 50 cm. The articulatory movements were recorded with an NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada). Eight channels of kinematic data were recorded. The first two came from a reference sensor glued to eyeglass frames without lenses. This served as the origin of the coordinate system that was used to measure articulator movements while correcting for head movements. Six channels of articulator data were collected by attaching 3 mm sensor coils at midline to the following structures: three sensors on the tongue (i.e., tongue back (TB), tongue mid (TM) and tongue front (TF)), mandibular central 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 different for individual speakers in order to maintain a consistent distance between the incisors for each participant. Tongue depressors were cut into 10 mm pieces and placed in between the incisors in order to create the 10 mm inter-incisal gap for each participant and to hold this position as the impression material cured.

**Speech Stimuli**

The speech targets were produced as part of the phrase, *The blue spot is on the black key again.* The stimuli being measured were the nuclei of four of the words; the high back vowel in *blue*, the low back vowel in *spot*, the low front vowel in *black*, and the high front vowel in *key*. The experimenter modeled the task, and the participant was instructed to repeat the stimulus phrase five times with a breath between.

**Procedure**

Each participant produced the speech stimuli prior to the sensors being glued to the articulators to allow acoustic recordings of typical speech. A calibration recording was made using a sound level meter positioned 50 cm from the participant. The participant was instructed to sustain an /ɑ/ vowel for 5 seconds and the experimenter noted the dB display on the meter. This was done to provide a known intensity for the correction of dB levels during subsequent acoustic analysis. 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 these 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 it was inserted (post-BB).

**Kinematic Analysis**

A custom Matlab (The Mathworks, Inc., 2018) application was created to segment the longer recording into individual target words which were saved as separate files (i.e., *blue*, *spot*, *black*, and *key*). An additional custom Matlab application was created to further segment the recordings to extract each vowel (e.g., /u/, /ɑ/, /æ/, /i/). This application extracted the positions of the tongue, lips, and jaw from the x/y positions of each sensor in the sagittal plane. The relative contributions of the jaw, tongue and lower lip were computed by decoupling their movements.

This decoupling required an estimation of the vertical movement of the jaw at each sensor location, given the rotational movement of the mandible. Since jaw movement was recorded from a sensor on the lower incisors, the distance of each sensor from the temporomandibular joint (TMJ) was estimated as follows. Earlier work on jaw decoupling (Westbury, Lindstrom, & McClean, 2002) has used an estimate of 110 mm as the average distance from the TMJ to the lower incisors in adults. The present analysis extracted the tongue sensor positions from the kinematic recording of the sustained /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 mm 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. Once the movements of the jaw and tongue were decoupled, analysis was undertaken to measure lip aperture and tongue height during each of the participant's vowel tokens, although the current report focuses on the positions of the three tongue markers.

The positions of the tongue markers (TB, TM, TF) for each vowel production were plotted with x and y axes representing their horizontal and vertical coordinates in space (Figure 1). The plotted points representing each participant's x/y coordinates for each vowel were then used to calculate the kinematic vowel articulation index (kVAI), the kinematic metric that was used to represent lingual excursion. The kVAI for the four corner vowels was determined by the following equation $(y_u + y_i + x_i + x_{æ}) / (y_{æ} + y_{ɑ} + x_{ɑ} + x_u)$. The kVAI decreased with vowel kinematic centralization and increased with expansion. The kVAI was averaged for the vowel tokens in either the pre-BB or post-BB condition, separately for each of the three tongue markers.

**Acoustic Analysis**

A custom Matlab application was used to segment the corner vowels from each of the words (i.e., *blue*, *spot*, *black*, *key*). After these vowels were segmented and saved as individual

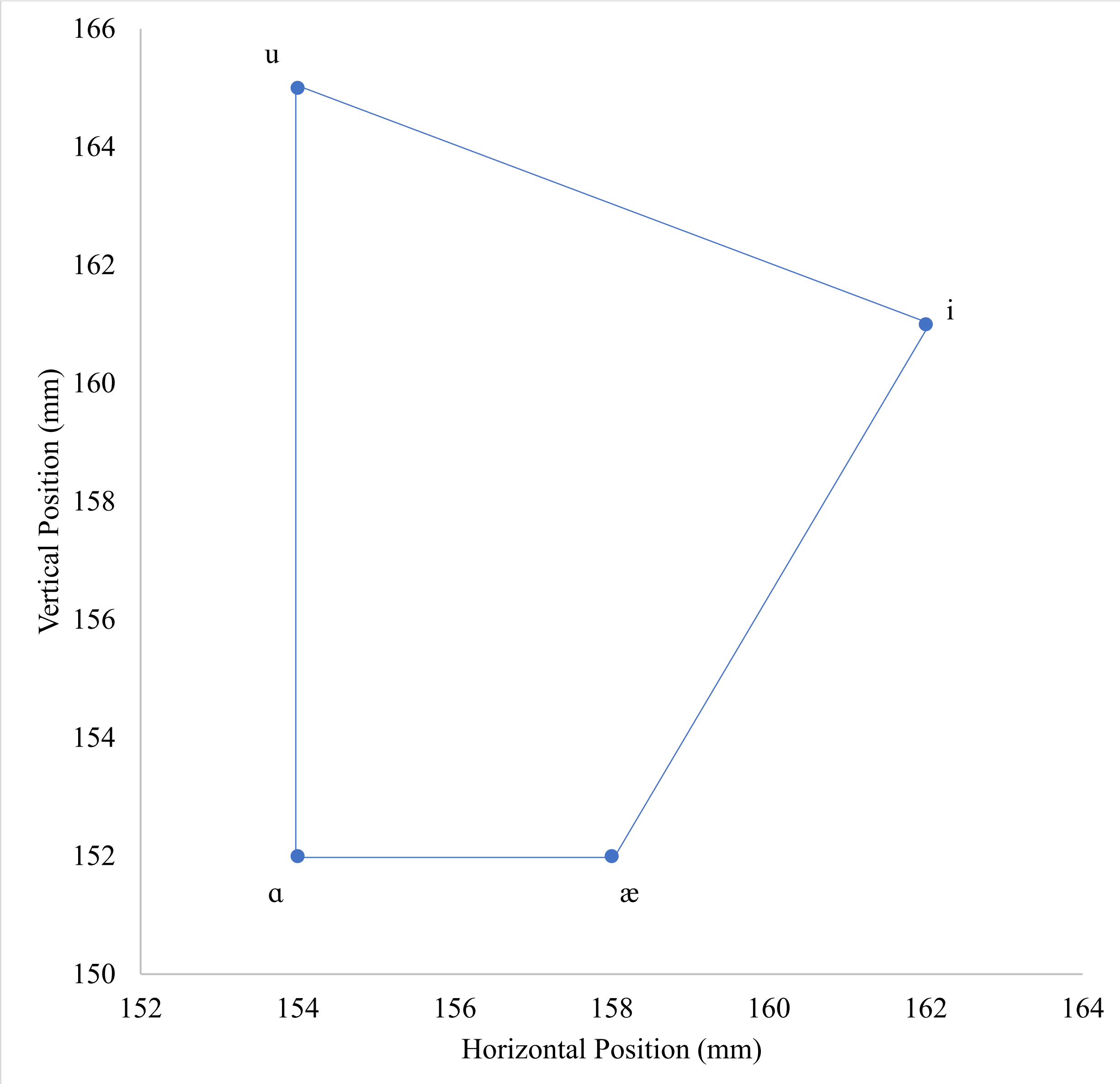



*Figure 1.* A kinematic quadrilateral formed from the x/y coordinates of each vowel.

wav files, they were imported into Praat (Boersma & Weenink, 2013) where the first and second formants were extracted. The average F1 and F2 values from the middle 50% of each vowel token were used to compute the vowel space area (VSA) and acoustic vowel articulation index (VAI) for each condition (i.e., pre-BB or post-BB). The VSA represents the area enclosed

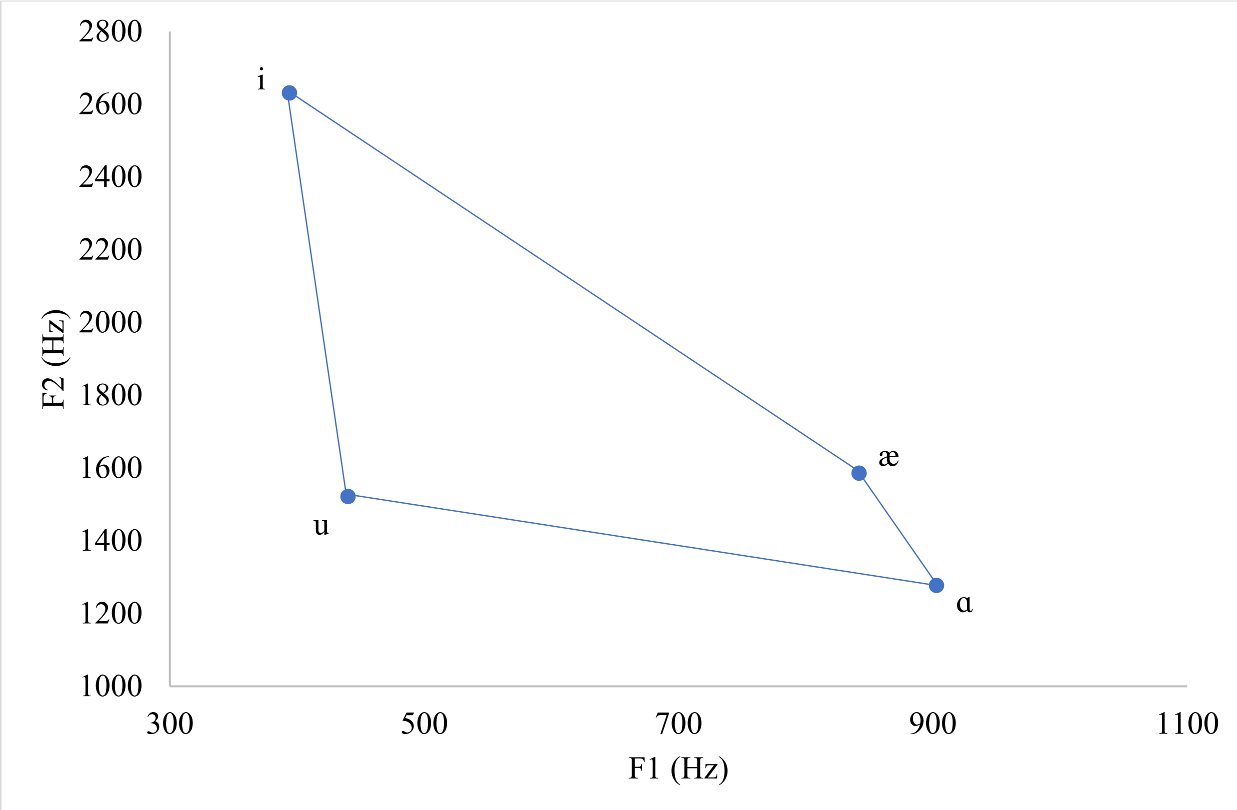



*Figure 2.* Vowel quadrilateral formed from the first and second formant coordinates

in Hz$^2$ by the coordinates formed from plotting F1 and F2 of each corner vowel on a graph as shown in Figure 2. The VSA is a traditional vowel space metric and was used here to compare the speakers' vowel acoustics before and after bite block insertion. A smaller area metric represents a more compact vowel space, which itself reflects reduced articulatory excursions (Berisha, Sandoval, Utianski, Liss, & Andreas, 2013).

An acoustic equivalent of the kVAI ratio was also computed, called the VAI. Using the first two formants of each vowel, the acoustic VAI was calculated using a similar formula as the one used to find kVAI: $(F2_{æ} + F2_{i} + F1_{ɑ} + F1_{æ}) / (F2_{u} + F2_{ɑ} + F1_{i} + F1_{u})$. As was the case for the kVAI, the smaller ratio of the VAI represents a more centralized acoustic vowel space as the formants reflect lingual articulation closer to the middle of the mouth. The intent of using the vowel space area and the acoustic vowel articulation index is to compare the pre- and post-BB conditions and how the acoustics are affected as a result of the perturbation.

**Statistical Analysis**

The independent variables were the participant sex and whether the stimuli were spoken before or after bite block insertion. The dependent variables were the acoustic vowel articulation index, the acoustic vowel space area, and the kinematic vowel articulation index for each of the three tongue sensors (TB, TM, TF). A repeated measures ANOVA in SPSS (International Business Machines Corporation, 2017) was used to test for significant changes in the dependent variables following bite block insertion. Speaker sex was included as a factor to test for any male/female differences in performance. The significance level for the analysis was $p < 0.05$. The data from one male and one female participant from the mid-tongue sensor were removed from statistical analysis due to tracking errors during data collection. All other signals were available for all 20 participants.

## Results

A repeated measures ANOVA was used to analyze the effect of bite block insertion and speaker sex on the acoustic and kinematic dependent variables (see Table 2). No bite block by sex interactions were found. However, for several variables there was a between-subjects effect for speaker sex. The descriptive statistics for the dependent measures are displayed in Table 1 and in Figures 1-5. The acoustic (formant-based) VSA and VAI decreased significantly after insertion of the bite block. The VAI based on the kinematic sensors on the back of the tongue (TB VAI) and middle of the tongue (TM VAI) also decreased significantly in the bite block condition. There was no significant change for the VAI based on the kinematic sensor on the front of the tongue (TF VAI). When considered separately, the VAI effect sizes following the

Table 1

*Descriptive Statistics for the Acoustic and Kinematic Measures in Pre- and Post-BBI Conditions*

| | | **Pre-BBI** | | **Post-BBI** | |
|---|---|---|---|---|---|
| | Gender | Mean | SD | Mean | SD |
| **Acoustic VSA** | Female | 345242.00 | 104970.00 | 235846.00 | 90378.00 |
| | Male | 235310.00 | 74292.00 | 186250.00 | 84479.00 |
| **Acoustic VAI** | Female | 1.65 | 0.10 | 1.50 | 0.16 |
| | Male | 1.58 | 0.08 | 1.49 | 0.13 |
| **Tongue Back VAI** | Female | 1.04 | 0.02 | 1.02 | 0.02 |
| | Male | 1.08 | 0.02 | 1.06 | 0.03 |
| **Tongue Middle VAI** | Female | 1.03 | 0.02 | 1.02 | 0.01 |
| | Male | 1.06 | 0.02 | 1.05 | 0.03 |
| **Tongue Front VAI** | Female | 1.02 | 0.02 | 1.01 | 0.01 |
| | Male | 1.04 | 0.02 | 1.04 | 0.03 |

*Note.* BBI = bite block insertion; VSA = vowel space area (in $Hz^2$); VAI = vowel articulation index (unitless ratio).

Table 2

*Repeated Measures ANOVA Main Effects of Bite Block Insertion on the Acoustic and Kinematic Measures*

| | df | *F* | *p* | $\eta p^2$ |
|---|---|---|---|---|
| Acoustic VSA | 1,18 | 16.373 | 0.001 | 0.476 |
| Acoustic VAI | 1,18 | 17.067 | 0.001 | 0.487 |
| Tongue Back VAI | 1,18 | 13.245 | 0.002 | 0.424 |
| Tongue Middle VAI | 1,16 | 5.858 | 0.028 | 0.268 |
| Tongue Front VAI | 1,18 | 2.957 | 0.103 | 0.141 |

*Note.* VSA = vowel space area; VAI = vowel articulation index; $\eta p^2$ = effect size.

bite block placement were greatest for the tongue back sensor, lower for the tongue middle sensor, and smallest for tongue front sensor.

A significant between-subjects effect was observed for speaker sex for the acoustic VSA, $F(1, 18) = 5.264$, $p = 0.034$, $\eta p^2$ .226, with higher values for females (see Figure 3). There was a significant between-subjects effect for speaker sex for TB VAI, $F(1, 18) = 18.036$, $p < 0.001$, $\eta p^2$ .501, with much higher values for males (see Figure 5). A between-subjects effect was also observed for speaker sex for TM VAI, $F(1, 16) = 16.140$, $p = 0.001$, $\eta p^2$ .502, with much higher values for males (see Figure 6). Lastly, a significant between-subject effect was observed for speaker sex for TF VAI, $F(1, 18) = 10.453$, $p = 0.005$, $\eta p^2$ .367, with higher values for males (see Figure 7).

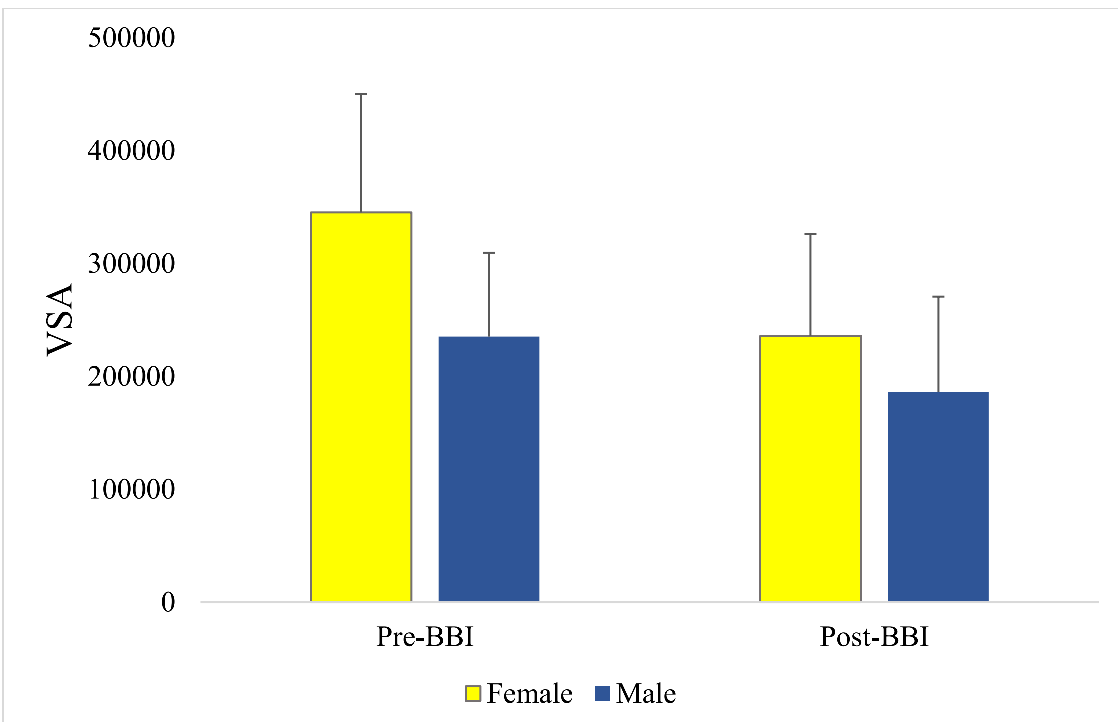



*Figure 3.* Means and standard deviations of the acoustic VSA (in $Hz^2$) for women and men before and after bite block insertion.

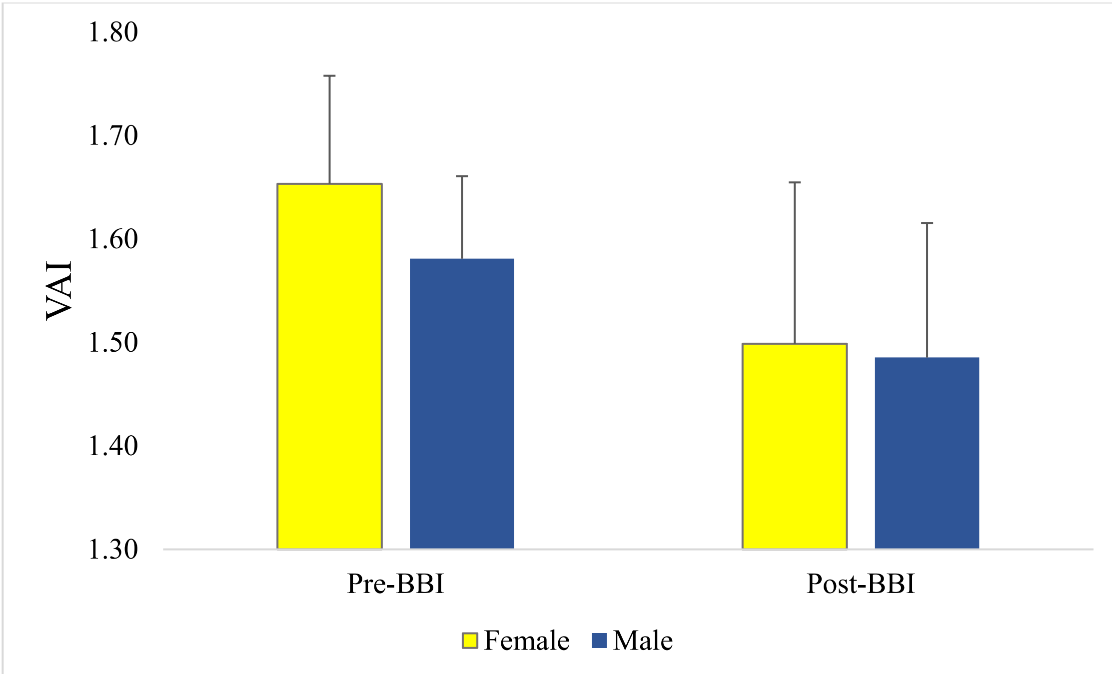



*Figure 4.* Means and standard deviations of the acoustic VAI for women and men before and after bite block insertion.

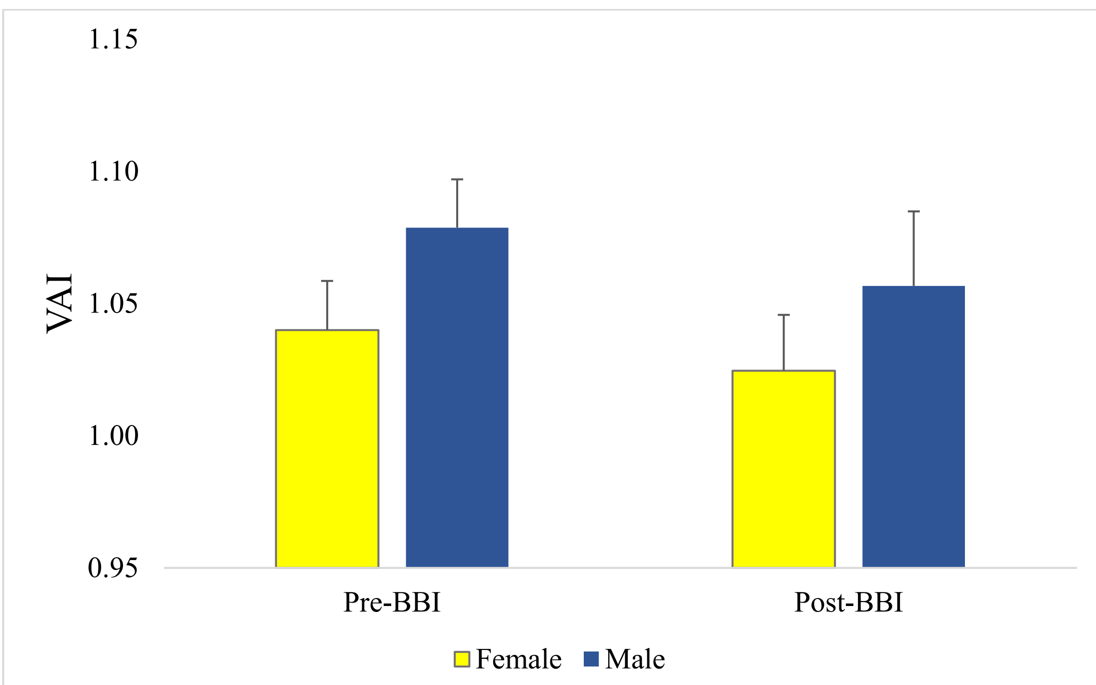



*Figure 5.* Means and standard deviations of tongue back VAI for women and men before and after bite block insertion.

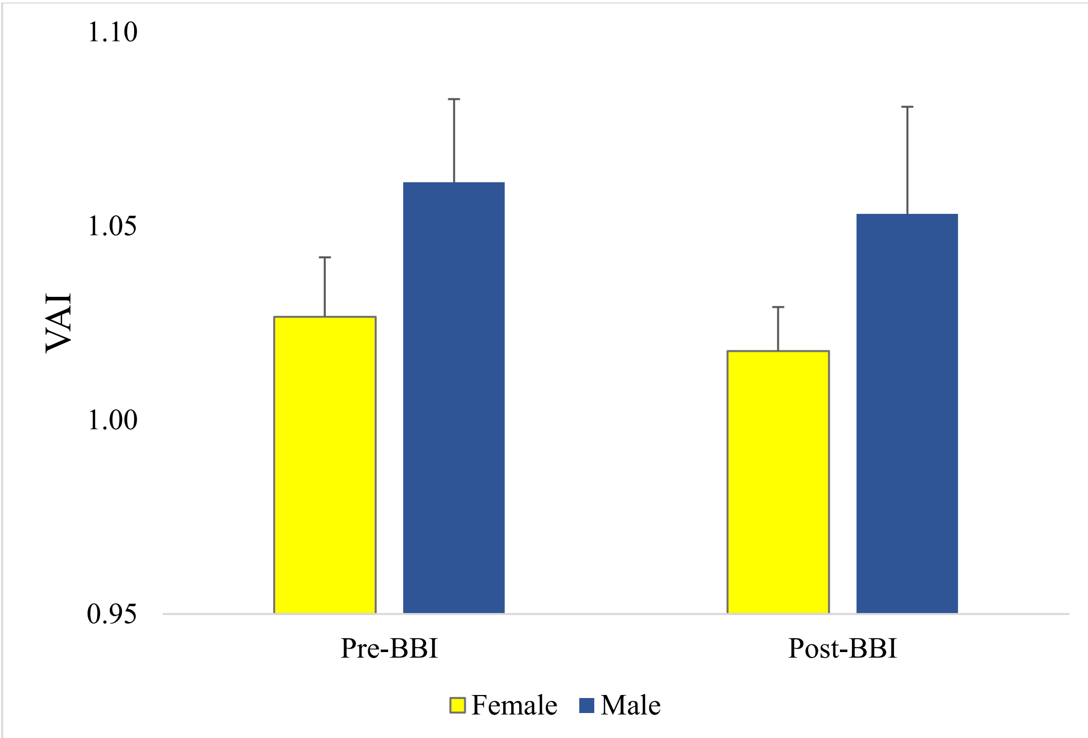



*Figure 6.* Means and standard deviations of tongue middle VAI for women and men before and after bite block insertion.

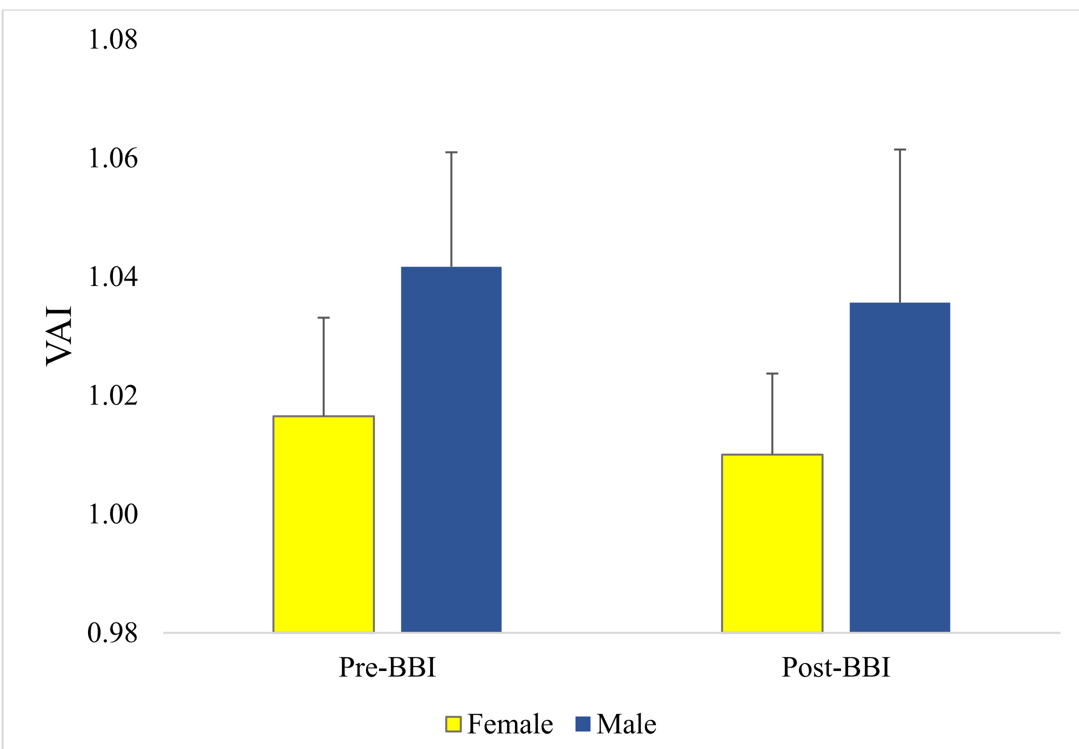



*Figure 7.* Means and standard deviations of tongue front VAI for women and men before and after bite block insertion.

## Discussion

This study examined the acoustic and articulatory kinematic changes that occur as a result of bite block insertion. Significant acoustic and kinematic effects were observed as the speakers attempted to compensate for the perturbation.

### Kinematic Compensation

Sizeable kinematic pre- and post-bite block differences were observed for the kVAI metric, the unitless ratio resulting from the formula that takes into account the x and y coordinates of each of the four corner vowels. These changes were observed in the kVAI metrics for the back and middle of the tongue. Smaller pre- and post-BB differences were observed for the kVAI of the front of the tongue, and thus the effect size of the perturbation was much smaller. The comparison of these ratios before and after bite block insertion showed that positioning of TB and TM was significantly affected by the perturbation, preventing these parts of the tongue from reaching the same positions as without the bite block. The tongue front, on the other hand, was also affected, but not enough that it failed to reach the position necessary for adequate vowel production.

Namasivayam et al. (2008) kinematically measured the speech of people who stutter and people with typical speech. They produced two nonword bisyllabic stimuli in the context of other real word stimuli, both in free and bite block conditions at normal and fast rates. From the sensor coils attached to the participants' articulators, Namasivayam et al. found that both groups of speakers adapted to the bite blocks after insertion. Compensation to the perturbation was also observed in the current study through significant changes in kVAI for vowel production. Namasivayam et al. concluded that strategies to compensate for articulatory perturbation were comparable in both disordered and typical speakers. Similarly, the typical speakers in the present study exhibited compensation for perturbation by adjusting their articulation; this was evidenced by the decrease in kVAI.

In this study, articulatory compensation was measured through comparison of relative tongue positioning during vowel production by way of the kVAI metric. The change in this metric for each part of the tongue varied according to amount of freedom the portion (i.e., TB, TM, or TF) of the tongue is allowed anatomically. The posterior attachment between the tongue root and the mandible allows the front of the tongue to move more freely. This biomechanical coupling allows a greater range of motion of the front of the tongue, meaning it is better able to compensate for a bite block perturbation than the TB or TM. The speakers needed to compensate for the lower jaw position resulting from the bite block by independently raising the tongue more than they did for vowel production without the perturbation. As noted above, the TF was more free than the TB or TM to achieve the correct posture for vowel production once the bite block was inserted.

There were also between-subjects effects for speaker sex for the kinematic VAI for all three points on the tongue (TB, TM, and TF), with higher values for men than women on all points. This is likely due to the typically larger size of the oral cavity for men, meaning that the tongue needs to make larger movements to accomplish the same vowel output.

**Acoustic Compensation**

Our findings reveal that the acoustics of the corner vowels were affected significantly after bite block insertion. The changes in the acoustic metrics of VSA and VAI are based on comparing two quadrilaterals of each of the four corner vowels, plotted with axes of F1 horizontally and F2 vertically in the pre- and post-BB conditions. The VAI, a ratio calculated from the first two formants of all four vowels, showed that the acoustics overall became more centralized; this represented more reduced articulatory movements after bite block insertion. Likewise, the VSA, calculated from the areas of these quadrilaterals became significantly smaller with the bite block in place. The decrease in the VSA denotes a neutralization of the acoustics, as the formants of the corner vowels of the quadrilateral move towards each other. Similar findings were reported by Campbell (1999) in a study of bite block speech. She reported that the F2 of the vowels in the words “heat” and “hat” significantly decreased with bite block insertion. This reflected a less advanced tongue posture for these vowels.

A study by Stevens et al. (2011) measured the effects of perturbation on the acoustics of one corner vowel in particular (/i/). The participants in this study were recorded saying 35 sentences (three of which were analyzed for speech intelligibility and normalcy) before rapid palatal expanders (RPE) placement to analyze the effect that orthodontic perturbation may have on the speech stimuli perceptually and acoustically. The first formant for the vowel /i/ increased and the second formant decreased, resulting in a more centralized vowel. This in congruent with acoustic results of the current study because the decreased VAI and VSA after bite block insertion also resulted from the centralization of the corner vowels.

A between-subjects effect for speaker sex for the VSA for the production of the vowels was found, with higher values for women than men. This is likely due to the smaller vocal tract size of women compared to men, which would resonate higher frequencies overall (Behrman, 2018).

**Kinematics and Acoustics Considered Together**

A valuable contribution of the current study is the measurement of both kinematic and acoustic metrics with and without a bite block perturbation. When considering how these metrics changed in bite block speech, the acoustic metrics of VAI and VSA had larger effect sizes than the kinematic metrics (kVAI) of the three points on the tongue. This suggests that although the participants articulated differently to compensate for the perturbation, the compensation was insufficient to completely overcome the bite block effect, because the acoustics still changed significantly.

Jacks (2008) conducted a study comparing the acoustic effects of a bite block on speakers with apraxia of speech (AOS) and healthy controls. The results indicated that all of the speakers had incomplete compensation to the bite block, but that speakers with AOS and aphasia experienced greater changes in their formants than those with typical speech production. Jacks concluded that all speakers showed a decrease in perceptual accuracy of a relatively similar magnitude, but that the vowel acoustics of the speakers with AOS changed more with the perturbation. It is possible that kinematic measures could have revealed the mechanism behind the acoustic disparity between subject groups and whether apraxia of speech, a motor planning disorder, involved greater differences in the kinematic metrics as well. The current study suggests that incomplete articulatory compensation to perturbation can result in acoustic differences in bite block speech.

**Limitations of the Current Study and Directions for Future Research**

The stimulus phrase used during data collection (*The blue spot is on the black key again*) was selected because previous acoustic studies have used it to analyze the corner vowels in a sentence context (Russell, 2010). However, the different consonant-vowel contexts in which each corner vowel was spoken allowed for potentially differing coarticulatory effects. This was especially challenging during segmentation when the vowels were difficult to parse from voiced consonants in words like *blue* and *black*. The stimulus sentence was helpful for the study of vowels in a natural syntactic context, but this meant that vowels were not produced in identical phonetic contexts. A less natural but more controlled stimulus context might involve placing the vowels between voiceless consonants, as in the words *hoop*, *hap*, *hop*, and *heap*. This would make segmentation more precise and vowel production more consistent, which could potentially yield slightly different results.

Another unanticipated limitation to the study was that some of the participants were inconsistent while biting down on the bite blocks. This inconsistency meant that the jaw was not fully stabilized, and that the mandible could have contributed slightly to vowel production in the bite block condition. This limitation could be eliminated in further research with more explicit instruction to the participants to remind them that they should be biting down post-bite block insertion throughout the entire sentence, and not allow the jaw to move at all during speech.

Further research using additional recordings from this study could involve analyzing the kinematic and acoustic data as the participants adapted to the perturbation over time. The current study analyzed a subset of the data that were collected, examining the VAI and VSA immediately prior to and following bite block insertion. Future researchers could expand upon the results of this study and track the extent and timing of acoustic and kinematic changes as adaptation to the bite block continues over time.

**Conclusion**

This study examined changes in vowel production following the insertion of a bite block. It was predicted that bite blocks would affect both the kinematic and acoustic measures as the participants attempted to compensate for the perturbation. We have shown that the speakers adjusted their articulatory behavior, but that these kinematic changes were not enough to maintain unchanged vowel acoustics after bite block insertion.

References

Behrman, A. (2018). *Speech and Voice Science* (3rd ed). San Diego, CA: Plural Publishing Inc.

Berisha, V., Sandoval, S., Utianski, R. L., Liss, J. M., & Andreas, S. (2013). Characterizing the distribution of the quadrilateral vowel space area. *Journal of the Acoustical Society of America, 135*, 421-427. doi:10.1121/1.4829528

Boersma, P., & Weenink, D. (2013). Praat: Doing Phonetics by Computer (Version 5.3.39) [Computer Program]. Retrieved 8 May 2019 from http://www.praat.org/

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

Campbell, M. M. (1999). *Articulatory compensation for a bite block, with and without auditory feedback, in hearing and hearing-impaired speakers* (Doctoral dissertation). Retrieved from ProQuest Dissertations & Theses Global: Social Sciences. (Order No. 9917636).

DeJarnette, G. (1988). Formant frequencies (F1, F2) of jaw-free versus jaw-fixed vowels in normal and articulatory disordered children. *Perceptual and Motor Skills, 67*, 963-971. doi: 10.2466/pms.1988.67.3.963

Dromey, C., Hunter, E., & Nissen, S. L. (2018). Speech adaptation to kinematic recording sensors: Perceptual and acoustic findings. *Journal of Speech, Language, and Hearing Research, 61*, 593-603. doi: 10.1044/2017_JSLHR-S-17-0169

Gay, T., Lindblom, B., & Lubker, J. (1981). Production of bite-block vowels: Acoustic equivalence by selective compensation. *Journal of the Acoustical Society of America, 69*, 802-810. doi: 10.1121/1.385591

International Business Machines Corporation. (2017). IBM SPSS Statistics for MacIntosh (Version 25.0) [Computer Software]. Armonk, NY: International Business Machines Corporation.

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

Kent, R. D. (1996). Hearing and believing: Some limits to the auditory-perceptual assessment of speech and voice disorders. *American Journal of Speech-Language Pathology, 5*, 7-23.

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

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*, 426-440. doi: 10.1121/1.4939894

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

Namasivayam, A. K., van Lieshout, P., & De Nil, L. (2008). Bite-block perturbation in people who stutter: Immediate compensatory and delayed adaptive processes. *Journal of Communication Disorders, 41*, 372-394. doi: doi:10.1016/j.jcomdis.2008.02.004

Perkell, J. S., Matthies, M. L., Svirsky, M. A., & Jordan, M. I. (1993). Trading relations between tongue-body raising and lip rounding in production of the vowel /u/ - a pilot motor equivalence study. *Journal of the Acoustical Society of America, 93*, 2948-2961. doi: 10.1121/1.405814

Russell, B. A. (2010). Using manual tension reduction treatment in treating pediatric functional dysphonia. *Contemporary Issues in Communication Science and Disorders, 37*, 131-140.

Stevens, K., Bressmann, T., Gong, S., & Tompson, B. D. (2011). Impact of a rapid palatal expander on speech articulation. *American Journal of Orthodontics and Dentofacial Orthopedics, 140*, e75. doi:10.1016/j.ajodo.2011.02.017

The MathWorks, Inc (2018). MATLAB and Statistics Toolbox Release (2018b) [Computer Software]. Retrieved 8 May 2019 from https://www.mathworks.com/products/statistics.html

Westbury, J., 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*, 651-662. doi: 10.1044/1092-4388(2002/052)

APPENDIX A

**Annotated Bibliography**

Behrman, A. (2018). *Speech and Voice Science*. 3rd ed. San Diego, CA: Plural Publishing Inc.

*Relevance to the current work:* General information regarding formants and how the first two formants are used to identify vowels is relevant to the current work because the work references vowel acoustic measures.

Berisha, V., Sandoval, S., Utianski, R. L., Liss, J. M., & Andreas, S. (2013). Characterizing the distribution of the quadrilateral vowel space area. *Journal of the Acoustical Society of America, 135*, 421-427. doi:10.1121/1.4829528

*Objective:* The researchers' objective was to describe the characteristics of the quadrilateral vowel space area (VSA).

*Method:* 630 participants from eight different dialectal regions participated in this study. Participants were recorded saying each of the four corner vowels (i.e., /i/, /æ/, /ɑ/, /u/) and the first two formants of each vowel were used to compute the VSA. These VSA values were compared with intelligibility as well as the theoretically predicted values from the Hillenbrand and TIMIT data sets.

*Results:* The theoretically predicted data from the Hillenbrand and TIMIT data sets were similar to the data resulting from this study.

*Conclusion:* As a result of the similar data sets, the researchers concluded that the use of VSA in vowel formant analysis is validated.

*Relevance to the current work:* How VSA is calculated from the vowel quadrilaterals is discussed within the current 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*, 457- 476. doi:10.1007/s00221-006-0848-1

*Objective:* The objective of this study was to observe motor equivalent strategies in speakers when perturbed by a palatal prosthesis.

*Method:* Six native German-speaking adults (two males, four females) participated in the study. The speakers, who had experienced orthodontic work within the last 1-3 years, were given a dental prosthesis that they were to wear all day for two weeks. Kinematic data were collected on three different occasions throughout the two weeks. Sensor coils were attached to the jaw, lips, and three different parts of the tongue (tip, middle and back). Their articulatory movements were recorded using an electromagnetic articulograph while producing the nonsense word /shaxa/ in varying conditions (without perturbation, with perturbation and auditory masking, with perturbation and no masking, without perturbation after two weeks).

*Results:* Adaptation, consistent with the original hypotheses, was observed in all speakers even when masking disrupted auditory feedback.

*Conclusion:* Motor equivalent strategies were employed by all speakers experiencing perturbation. The ways the speakers modified their articulation throughout the duration of the study differed between speakers and some adapted better to the perturbation than others.

*Relevance to the current work:* The current work discusses motor equivalence and the possibility of achieving a similar acoustic output with adjusted articulation.

Campbell, M. M. (1999). *Articulatory compensation for a bite block, with and without auditory feedback, in hearing and hearing-impaired speakers* (Doctoral dissertation). Retrieved from ProQuest Dissertations & Theses Global: Social Sciences. (Order No. 9917636).

*Objective:* The author's goal was to investigate the role of auditory feedback in articulatory compensation when speech is perturbed using a bite block.

*Method:* Four groups of people participated in this research: adults with normal hearing, four-year-old children with normal hearing, adults with congenital profound hearing loss, and adults with severe hearing loss. The participants produced 3 vowels (ie., /i, æ, ɪ/) within the context of the word "hVt" in the carrier phrase "say hVt again" in four conditions of varying masking and perturbation via bite block. Acoustic measurements of first and second formants were taken for each vowel and compared to control conditions to account for articulatory compensation. Intensity and fundamental frequency were also measured.

*Results:* Adults with normal hearing and those with severe hearing loss compensated substantially, but not completely, for the bite block perturbation. Results showed that F2 for these groups was lowered during the bite block trial and masking trial. F2 was significantly lowered during the trial with both the bite block and the auditory masking. F2 for "heat" and "hat" were lowered significantly with bite block and auditory masking more so than for "hit;" however F1 for "hit" was raised significantly compared to the control condition but had no significant effect on perception. The children who participated did not demonstrate adult-like abilities to compensate despite having relatively smaller bite blocks. Adults with congenital profound hearing loss overcompensated for bite block perturbation with more anterior tongue position and variable tongue height.

*Conclusion:* The researchers concluded that articulatory compensation occurs for all, including those with hearing loss, but the extent to which they compensate and how they compensate varies. They suggested that this articulatory compensation is learned at a crucial point during speech development, but that if acoustic feedback is not available during this period, articulatory compensation occurs in response to tactile and proprioceptive input.

*Relevance to the current work:* Articulators adjust when perturbed by bite blocks, following patterns of lowering certain formants of vowels while raising other formants of other vowels. The current work focuses on two out of the three of these vowels and comparisons to the hearing participants of this study will provide an interesting reference.

DeJarnette, G. (1988). Formant frequencies (F1, F2) of jaw-free versus jaw-fixed vowels in normal and articulatory disordered children. *Perceptual and Motor Skills, 67*, 963-971. doi: 10.2466/pms.1988.67.3.963

*Objective:* The authors' goal was to investigate compensatory articulation of perturbed productions of vowels using bite blocks compared to unconstrained productions.

*Method:* Fifteen male participants (five adults with typical speech abilities, five children with typical speech abilities, and five children with articulatory deficits) were recorded producing the vowels /i, æ, a, u/ in a block design randomized order. Each vowel was produced 12 times with and without bite block conditions. Acoustic measures of the first and second formants were taken and compared between conditions.

*Results:* The results indicated normal formant production between free and bite block trials of vowel production. The lowering of the second formant was consistent with being within a range of normal for each respective vowel. This result was consistent across speaking condition (i.e., bite block or free), vowel, or speaker group (i.e., whether or not the speaker had disordered speech, adult or child). The researchers reported that the coefficient of variation (CV) for all speakers across vowel formants was extremely small and therefore unremarkable.

*Conclusion:* Though the results indicated that the formants from each vowel production were within normal ranges, the researchers drew some interesting conclusions; notably that F1 was affected significantly by the presence of the bite blocks for /a/ when none of the other vowels were and that F2 was higher in the articulatory disordered group of children compared to the control group of children. They conclude overall that speech-motor compensation for perturbation is ultimately context-dependent and that perhaps individual vowels would not vary too much from unconstrained vowels in typical formant range.

*Relevance to the current work:* The same vowels that were measured acoustically for this study are also being measured in the current work. The rationale for context-dependent compensation is also justified in the current study from these results.

Dromey, C., Hunter, E., & Nissen, S. L. (2018). Speech adaptation to kinematic recording sensors: Perceptual and acoustic findings. *Journal of Speech, Language, and Hearing Research, 61*, 593-603. doi: 10.1044/2017_JSLHR-S-17-0169

*Objective:* This study was conducted to determine the amount of time needed to adjust to the electromagnetic sensor coils used in kinematic recordings by analyzing speech perceptually and acoustically.

*Method:* Twenty native English speakers were recorded reading aloud stimulus sentences immediately following sensor coil attachment as well as after 5, 10, 15, and 20-minute intervals of adaptation to the sensors. These recordings were then rated by native English speakers for precision. Fricatives from the recordings were isolated and analyzed with Praat for spectral changes due to the placements of the coils on the articulators.

*Results:* The results showed that after a substantial precision decrease when the sensors were places, the perceived precision of the sentences increased over time until the 10-minute mark where the ratings plateaued. Acoustically, the speakers never fully adapted to the sensors—the spectral measures of the segmented fricatives differed from the pre-attachment values for the entire 20 minutes of the experiment.

*Conclusion:* The researchers concluded that 10 minutes is a sufficient amount of time for adaptation to electromagnetic sensor coils for adequate perceptual precision.

*Relevance to the current work:* The perceived perturbation of speech during kinematic recordings is a concern of the current study. This study outlines the effects electromagnetic sensor coils have on speech perceptually and acoustically.

Gay, T., Lindblom, B., & Lubker, J. (1981). Production of bite-block vowels: Acoustic equivalence by selective compensation. *The Journal of the Acoustical Society of America, 69*, 802-810. doi: 10.1121/1.385591

*Objective:* The objective of this study is to assess what native speakers of English do to compensate for articulatory obstacles, or "motor equivalence."

*Method:* Five adult males with normal hearing and typical speech were prompted to produce four Swedish vowels (/i, a, u, o/) in series of "triads" where they produced the isolated vowels isolated 3 times in a row. The vowels were measured acoustically as well as viewed via x-ray. They were then instructed to produce the vowels with 22.5 mm bite blocks in between their molars to fix the jaw.

*Results:* Analysis of the still x-ray lateral frames of each participants' mouth displayed drastic articulatory reorganization where the tongue and lips are described as forming "supershapes" to attempt to compensate for perturbation. The tongue supershapes were more dramatic for high vowels and more dramatic lip rounding contributed to adaptation for /u/ only.

*Conclusion:* Vowel targets are coded neurophysiologically so that the articulators "know" how far to travel (becoming "supershapes") to reach an adequate vocal tract constriction for each vowel target.

*Relevance to the current work:* Similar compensatory strategies for achieving maximum constriction amid perturbation via bite blocks is studied in the current work.

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

*Objective:* The researcher's goal was to measure vowel production and adaptation to articulatory constraints (i.e., bite blocks) in adults with apraxia of speech (AOS) and aphasia.

*Method:* The researcher acoustically and perceptually measured the "idealized" versions of three vowels (i.e., /ɪ, æ, ɛ/) in isolated, one, two, and three-word contexts produced by 5 adults with aphasia and AOS as well as by 5 adults with typical speech production (healthy controls or HC). These recordings were then contrasted with the same utterances produced while the participants had bite blocks in their mouths.

*Results:* The results indicated that all adults had incomplete compensation to the bite block constraints, but that speakers with AOS and aphasia experienced greater separation of the formants in their vowel productions than those with typical speech production. Also, speakers with AOS and aphasia had impaired vowel production perceptually and acoustically according to the vowel accuracy criteria that they used to judge.

*Conclusion:* The researchers concluded that the bite block contributed to a decrease in accuracy for all adult speakers, but that speakers with AOS and aphasia had a greater vowel formant separation and were even less accurate perceptually. However, because both the healthy controls and speakers with AOS showed a decrease in accuracy of a relatively similar magnitude, the researchers hypothesized that neural feedback control systems are intact in speakers with AOS.

*Relevance to the current work:* The current work is also acoustically analyzing vowels in word contexts with healthy adults.

Kent, R. D. (1996). Hearing and believing: Some limits to the auditory-perceptual assessment of speech and voice disorders. *American Journal of Speech-Language Pathology, 5*, 7-23.

*Objective:* This study was conducted to identify some of potential limitations that could arise as a result of only using perceptual assessment in studies of voice disorders that are intended to distinguish between typical and disordered speakers.

*Method:* No experiment was conducted but rather the author identified several subjective problems with perceptual studies of speech and voice disorders that mainly contribute to reliability and validity errors.

*Results:* Some of the recommendations Kent made to minimize inter-judge reliability errors that result from perceptual analysis were: using reference samples that listeners in the study can refer to or being more stringent on the type of experience necessary for one to be a judge in a particular study.

*Conclusion:* The author concluded that understanding the weaknesses of auditory-perceptual analysis is key to understanding when it may be appropriate and when it is not. He asserted that there should be more standardization of how perceptual studies are conducted so that reliability and validity are maximized.

*Relevance to the current work:* This study supports the value of instrumental methods of speech analysis. The current study uses this reasoning to build the case for kinematic assessment.

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

*Objective:* The researchers' goal was to assess if a specific brand of dental retainers caused speech disturbance and if so, how long it took a person to fully compensate for the retainer's effects.

*Method:* Twelve adolescents, three males and nine females, with ages ranging from 11.11 to 18.03 years were given Hawley retainers to wear for 24 hours a day for 6 months, only to be removed for brushing their teeth. All participants were native monolingual Turkish speakers and their vowels (including /i, e, a, u/) were measured subjectively via an articulation test (using nonsense syllables) and also acoustically, objectively obtaining each vowels' first, second, and third formants. These measurements were taken on the first day, after one week, after four weeks, and after three months.

*Results:* Statistically significant disturbances were observed in consonants /ş/ and /z/, even after weeks of wearing the retainer. For vowels, the only statistically significant disturbances were observed with /i/ where the first three formants were all observed to decrease.

*Conclusion:* Temporary changes in speech occur as a result of perturbation from oral obstacles. These changes can be compensated for but the adaptation period can take anywhere from 1 week to 3 months.

*Relevance to the current work:* The current study focuses on how the articulators adapt to perturbation for similar vowels. The changes in the formants described in this study will be especially helpful.

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

*Objective:* The purpose of the study was to examine the relationship between acoustic (formant frequencies) and kinematic (using tongue x-y coordinates) space for vowels in female speakers.

*Method:* Thirteen healthy women were involved in the study. These participants were recorded through ten speech tasks via electromagnetic articulography (for kinematic data) and synchronized audio recordings (for acoustic data).

*Results:* Results showed that the first formant's variations correlated tightly with the tongue movement along the x dimension and that the second formant highly correlated with tongue movement in both x and y dimensions. However, these results were found only within intra-speaker analyses; when compared with other speakers, the correlations were weaker.

*Conclusion:* Idiosyncratic kinematic vowel space is likely linked with acoustic vowel space and other inferences, such as size of tongue working space, can be drawn for most speakers from such data. The first formant correlates with tongue height and the second formant correlates with more complex tongue movements along both axes.

*Relevance to the current work:* Kinematic and acoustic data for vowels will also be examined for healthy adult speakers. Formant-based measures will provided the necessary data for inferences about the correlation between tongue movement and acoustic data.

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

*Objective:* The purpose of this study was to compare the acoustic differences of fixed and free-mandible conditions.

*Method:* Fifteen French-speaking women free of speech and language disorders were recorded saying three vowels (/i, a, u/) in isolation and in word contexts with two voiceless fricatives and three voiceless stops. The participants repeated the stimuli ten times each in random order and were recorded pre-bite block insertion, immediately upon bite block insertion, and after a 15-minute conversation with the bite block inserted.

*Results:* The results indicated that the participants never fully compensated to the perturbation even after the 15-minute accommodation period. Small but significant differences in the acoustic measurements of the vowels and consonants were observed.

*Conclusion:* Adaptation to perturbation involving vowels may require error-based correction feedback systems in order to fully compensate for the speech disturbance. The same can be said for consonants, but the time required to compensate for vowels is much shorter than for consonants due to the comparatively open vocal tract and less articulator involvement needed to articulate vowels. Individual differences also play a part in each person's ability to adapt to perturbation.

*Relevance to the current work:* This study provides a basis of how certain vowels shift acoustically when perturbed with different sizes of bite blocks and how the adaptation takes place after a certain period of time. The current work also focuses on measuring articulatory vowel adaptation after a period of accommodation for the speaker.

Namasivayam, A. K., van Lieshout, P., & De Nil, L. (2008). Bite-block perturbation in people who stutter: Immediate compensatory and delayed adaptive processes. *Journal of Communication Disorders, 41*, 372-394. doi: doi:10.1016/j.jcomdis.2008.02.004

*Objective:* The goal for this study was to investigate the degree to which sensory feedback aids in motor equivalence. Given the theory that people who stutter demonstrate motor skill issues presumably due to poor sensory feedback, the researchers elected to immobilize the jaw movements of people who stutter (PWS) and people who do not stutter (PNS) to analyze if motor equivalence is still achieved in both populations and how long it may take them to compensate for bite block perturbation.

*Method:* Five adult male PWS and five adult male PNS participated in the study by producing two nonword bisyllabic stimuli in the context of other real word stimuli both in free and bite block conditions at normal and “fast” word reading paces. The participants had sensor coils attached to their articulators to measure the kinematic data of before, immediately after, and after a 10-minute compensation period of bite block insertion.

*Results:* Variability of coordination was found in both populations, especially at the fast speech rate.

*Conclusion:* Bite block perturbation did not exacerbate any supposed motor speech difficulties exhibited by PWS and sensory feedback motor control strategies are comparable in both PWS and PNS.

*Relevance to the current work:* Kinematic data from sensory coils attached to the articulators were used in this work; this approach is also used in the current work while examining vowels.

Perkell, J. S., Matthies, M. L., Svirsky, M. A., & Jordan, M. I. (1993). Trading relations between tongue-body raising and lip rounding in production of the vowel /u/ - a pilot motor equivalence study. *Journal of the Acoustical Society of America, 93*, 2948-2961. doi: 10.1121/1.405814

*Objective:* The researchers’ main goal was to determine the relative contributions of different articulatory structures’ movements in the production of speech. Specifically, the researchers chose the example of the vowel /u/, examining kinematically how the relationship between rounding the lips and posterior tongue height contributed to the vowel’s acoustic identity.

*Method:* Four American English male speakers were recorded reading ten different utterances. Kinematic sensors were attached to the upper lip, lower lip, the central incisors, the tongue body, bridge of the nose and upper incisors.

*Results:* A negative correlation between the raising of the tongue body and the rounding protrusion of the lips was documented for all but one of the speakers. 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.

*Conclusion:* The researchers concluded that the results of the study confirmed the presence of motor equivalence at least in the production of the vowel /u/. In other words, that there is a trading relationship between the degree to which one rounds the lips and the height to which one raises the tongue. /u/ can be produced without significant rounding of the lips by compensating with tongue height.

*Relevance to the current work:* Motor equivalence is discussed in the current work and the trading relationship of /u/ is used as an example of the type of compensatory articulation for perturbation that may be found when measured kinematically.

Russell, B. A. (2010). Using manual tension reduction treatment in treating pediatric functional dysphonia. *Contemporary Issues in Communication Science and Disorders, 37*, 131-140.

*Objective:* The objective of this study was to examine the effects of manual tension reduction treatment on functional dysphonia (FD) in pediatric clients.

*Method:* One six-year-old female client with FD was recorded speaking various stimuli including the phrase *The blue spot is on the key again* before manual tension reduction treatment, directly after treatment, and one year following treatment. Acoustic analysis and perceptual measures by three other clinicians were then conducted to examine vocal quality and the effect of the treatment.

*Results:* Overall voice quality normalized following treatment including the presence of strain, breathiness, pitch, and loudness. Normal acoustic measurements of jitter and shimmer were observed following treatment as well. After one year, the client showed no change in her ability to maintain normal vocal quality as observed directly after treatment.

*Conclusion:* The manual tension reduction treatment was successful in treating this pediatric client's FD, with her acoustic and perceptual characteristics of her voice returning to normal limits.

*Relevance to the current work:* The current study uses a similar stimulus phrase to analyze the acoustics of each corner vowel.

Stevens, K., Bressmann, T., Gong, S., & Tompson, B. D. (2011). Impact of a rapid palatal expander on speech articulation. *American Journal of Orthodontics and Dentofacial Orthopedics, 140*, e75. doi:10.1016/j.ajodo.2011.02.017

*Objective:* The main objective of this study was to assess the degree to which speech is perturbed by rapid palatal expanders (RPEs) and how adaptation occurs to the perturbation over time.

*Method:* 22 patients were recorded saying 35 sentences (3 of which were analyzed for speech intelligibility and normalcy) before RPE placement, after placement, during expansion, during retention, after removal, and 4 weeks after removal. Perceptual measures were assessed by 10 listeners who listened to the recordings and rated each sentence for how typical the speech sounded. The recordings were also assessed acoustically for the vowel /i/ and two other fricative sounds via speech analysis software.

*Results:* Unsurprisingly, speech deteriorated upon RPE placement and improved over time. The speech ratings improved after the removal of the RPE. Acoustically, the first formant for the vowel /i/ increased and the second formant decreased. This indicates a centralization of the vowel.

*Conclusion:* The researchers concluded that this research will be helpful for families of patients who need RPEs, proving that normalcy of speech can be achieved during treatment and quickly after RPE removal as well.

*Relevance to the current work:* Acoustic measurement of vowels is a central feature of the current work and comparison of the vowel /i/ will be an interesting point of reference between the two studies.

Westbury, J., 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*, 651-662. doi: 10.1044/1092-4388(2002/052)

*Objective:* The main objective of this study was to assess the accuracy of several different methods in successfully decoupling the tongue and lip movements from the movements of the jaw during speech. The methods used within the study were *translation-rotation* (TR) model, *only-translational* (OT) model, *only-rotation* (OR) model and *estimated-rotation* (ER) model.

*Method:* Kinematic sensors were attached to the articulators (jaw, lips, and tongue) of 44 young native English-speaking adults with no speech or language disorders. The participants then read the sentence *She had your dark suit in greasy wash water all year* and the kinematic data from all rotation models were compared with the TR method—often considered the gold standard for measuring the pitching rotation of the jaw.

*Results:* The results indicated that methods accounting for the pitching rotation of the jaw were more accurate in tracking articulator movements than those methods that did not account for the rotation. The ER method was found to have the least amount of positional errors in kinematic data as compared to the TR method.

*Conclusion:* When measured decoupled from the movement of the jaw, more specific information about the movements of the lips and tongue during speech becomes available. The ER method was found to be the most effective at accounting for jaw movements in all dimensions (not simply just translational and/or rotational).

*Relevance to the current work:* The best decoupling method from this study was used in the current study to separate the contribution of the jaw from the movements of the tongue and lips.

APPENDIX B

**Informed Consent**

# <u>Consent to be a Research Subject</u>

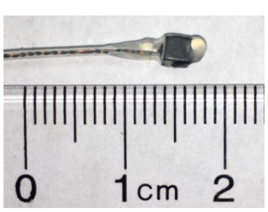
**Introduction**

This research study is being conducted by Christopher Dromey, a professor in the Department of Communication Disorders at Brigham Young University to determine how people's speech movements change when the movement of the jaw is temporarily restricted. He will be assisted by Madison McHaley, Tanner Low, and Michelle Olson, who are graduate students in the department. You were invited to participate because you are a native speaker of Standard American English with no history of speech or hearing disorders**.**

**Procedures**

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

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




tracking sensor

bite block

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

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

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

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

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

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

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

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

**Statement of Consent**

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

Name (Printed):________________ Signature:________________ Date:________

APPENDIX C

**Stimulus Phrases**

Stimuli- repeat 5 times every 2 minutes

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

I'm an owl that hoots

The blue spot is on the black key again