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Kinematic and Acoustic Adaptation to a Bite Block During Syllable Production

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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 purpose of the current study was to gain a better understanding of speech adaptation by examining kinematic and acoustic adaptation to bite block perturbation over time. Fifteen native American English speakers (7 female, 8 male) with no history of speech, language, or hearing deficits participated in the study. Custom bite blocks were created for speakers which created a 10mm interincisal gap when inserted. Speakers produced five repetitions of the sentence, *I say ahraw /əra/* (as part of a larger set) prior to bite block insertion, immediately following bite block insertion, 2-mintues post insertion, 4-minutes post insertion, 6-minutes post insertion, and immediately following bite block removal. Participants' speech was audio-recorded, and their lingual articulatory movements were measured with a Northern Digital Instruments Wave electromagnetic articulograph. The VC syllable /ɑɪs/ was analyzed kinematically from the midpoint of the /ɑɪ/ diphthong through production of /s/ using a custom Matlab application. Kinematic data were obtained via sensor coils placed in the tongue back, tongue mid, tongue front, jaw, lower lip and upper lip. Measures of displacement (mm), maximum velocity (mm/sec), and jaw contribution to the tongue and lower lip (mm) were taken during each recording. Spectral mean (Hz), standard deviation, skewness, and kurtosis were calculated for the central 50% of each /s/ production using acoustic analysis software. Kinematic analysis revealed no significant change in tongue measures upon bite block insertion or during the 6-minute adaptation period. In contrast, significant acoustic changes were observed upon bite block insertion and during the following 6 minutes, demonstrating adaptation over time. The changes observed in acoustic measures may have been a result of tongue shape changes and subsequent adaptations that were not detected via kinematic analysis. Future studies may provide further insight into the tongue's ability to compensate for bite block perturbation by examining the relationship between mandibular positioning and tongue shape.

Keywords: kinematics, acoustics, bite block, perturbation, adaptation, /s/

ACKNOWLEDGMENTS

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Lastly, I would like to thank my husband, Kade. He has somehow managed to love me through the stress and exhaustion of the past two years, and I simply could not be more grateful.

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DESCRIPTION OF THESIS STRUCTURE AND CONTENT

This thesis, *Kinematic and Acoustic Adaptation to a Bite Block During Syllable Production* 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, informed consent form information is found in Appendix B, and stimulus phrases are found Appendix C. Tables of descriptive statistics are located in Appendices D (kinematic) and E (acoustic).

This thesis format includes two reference lists: the first list contains references included in the journal-ready article, and the second list is located in Appendix A, titled “Annotated Bibliography.”

Introduction

Production of /s/

Children generally learn to produce the sounds of language, called phonemes, in a relatively predictable developmental trajectory. Although children do not learn to produce phonemes in a set order, certain phonemes are generally acquired earlier in development, and some are generally acquired later. For example, phonemes such as /m/ and /d/ are typically learned and produced at an early developmental stage. These early phonemes can be heard as children progress through the phases of babbling and begin to produce their first words. Other phonemes, however, take significantly longer to develop because of their complexity; they require more advanced motor control. One phoneme that takes most children many years to master is the fricative /s/. A cross-linguistic review of consonant acquisition performed by McLeod and Crowe (2018) indicated that approximately 10% of children do not master production of this phoneme until after age six, due to its complexity.

Production of a perceptually and acoustically typical /s/ requires great precision. To accurately produce /s/, the back of the tongue must form a narrow channel while the tongue blade either (a) rises to the alveolar region, where the tongue tip forms a constriction, or (b) lowers behind the inferior incisors, in which case the tongue dorsum rises to form a constriction (Borden & Gay, 1978; Hardcastle, Gibbon, & Jones, 1991). As air passes through both the channel and the constriction, frication, or high-frequency noise (above approximately 4 kHz) is produced to create the phoneme (Hughes & Halle, 1956). Small lingual movements, particularly when producing consonants like /s/, are known to cause significant acoustic and perceptual changes in phoneme production (Stevens, 1989). Therefore, when the place of constriction for the /s/ phoneme deviates slightly anteriorly, the sound becomes distorted by a frontal lisp, whereas when the place of constriction deviates posteriorly, the phoneme sounds like /ʃ/. Thus, the place of articulation for /s/ must be exact and consistent to result in accurate production. In fact, a study performed by Dromey and Sanders (2009) utilized palatometric data to measure within-speaker variability for lingual placement in the production of 15 consonants. They found that placement for the /s/ phoneme was one of the least variable, indicating that in order to produce a perceptually and acoustically correct /s/ sound, speakers must be extremely consistent in reaching exact lingual placement.

Because of the precision required to produce it, /s/ is a commonly misarticulated phoneme. This misarticulation may be the result of a speech sound disorder, a motor speech disorder, and/or the result of perturbation. Often, individuals who struggle to produce /s/ seek the help of speech-language pathologists with the intent of learning how to properly articulate this phoneme; thus, speech-language pathologists and speech scientists have a long history of studying the nature of this finnicky phoneme. A wide variety of studies, with a range of goals and aims, have been conducted over the years to learn more about the /s/ phoneme (Borden & Gay, 1978; Hughes & Halle, 1956; Tjaden & Turner, 1997). Although the aims of these studies have been diverse, each has required some means of evaluating and analyzing speech production. While speech scientists have developed many methods of evaluating speech production, most methods fit into one of three categories – perceptual, acoustic, and kinematic evaluations.

Evaluating Speech Production

Perceptual assessment is perhaps the most natural form of speech evaluation. It occurs in everyday situations as listeners perceive and evaluate, either consciously or unconsciously, the speech characteristics of others. Perceptual speech measures, because of their real-world nature, are often the most appropriate for use in clinical practice. As clinicians, speech-language pathologists often target speech intelligibility and naturalness, characteristics which are adequately evaluated using perceptual methods. Perceptual measures are also used frequently in research to examine speech production in a variety of settings. However, a limitation of perceptual measures in research studies is that they do not provide direct insight into the movements of speech which underlie those perceptible speech features. In order to obtain more precise, objective data, perceptual speech evaluation is commonly paired with either acoustic or kinematic measures in research (Dromey, Hunter, & Nissen, 2018; Flege, Fletcher, & Homiedan, 1988; McFarland, Baum, & Chabot, 1996).

Acoustic analysis of speech is widely used in studies that examine speech production (Aasland, Baum, & McFarland, 2006; Fowler & Turvey, 1980; McAuliffe, Robb, & Murdoch, 2007). Collecting acoustic data is a noninvasive way to closely analyze phonation, articulation, resonance, and other aspects of speech. Acoustic analysis of the first four spectral moments (mean, standard deviation, skewness, and kurtosis) has proven to be a reliable method of quantifying the frication noise from obstruent consonants (Forrest, Weismer, Milenkovic, & Dougall, 1988). These quantitative measures provide information regarding the precision of a speaker's articulatory gestures and are sensitive to consonant accuracy, changes with age, and disorder. However, because of motor equivalence, they cannot provide unambiguous insight into the specific movements of the articulators during speech tasks (Nittrouer, 1995). Motor equivalence refers to the fact that individuals have the potential to move their articulators in slightly different ways to produce acoustically equivalent phonemes. For example, Perkell, Matthies, Svirsky, and Jordan (1993) found that when typically speaking individuals produce the /u/ phoneme, they can covary their tongue height and lip rounding to produce acoustically equivalent vowels despite differences in their motor patterns. Motor equivalence, therefore, makes it impossible for speech scientists to reach specific conclusions regarding the movement patterns of speech based solely on acoustic data.

Kinematic measurement of speech provides access to that missing link. It enables speech scientists to collect data specifically on the articulatory movements used in speech production, thus overcoming the ambiguity inherent in the interpretation of acoustic data due to motor equivalence. Analysis of kinematic data allows speech scientists to understand motor behaviors and obtain a clearer picture of how the brain controls articulation during speech production. Tasko and Westbury (2002) proposed a system of defining and measuring speech movement events using kinematic measures, because they could "highlight both the underlying complexity of speech production and also its continuity" in a way that acoustic definitions and measures could not (Tasko & Westbury, 2002, p. 127). These advantages of kinematic speech measurement have made it an extremely valuable tool in a variety of speech studies. Despite its usefulness, this tool has been, and continues to be underused in studies of speech perturbation, which enable speech scientists to closely examine the process of speech adaptation.

Perturbation

For decades, speech scientists have been intentionally perturbing the speech of research participants to study the way humans adapt to interruption to their typical speaking patterns. The reason for this intentional perturbation is to better understand how individuals – both typical speakers and individuals with disordered speech – adapt to speech perturbation. Real-world perturbation can affect the speech of both typical and disordered populations in a variety of ways (e.g., dental appliances, medical procedures, etc.); therefore, as rehabilitation professionals, it is important to learn about how adaptation to speech perturbation occurs in order to facilitate that adaptation when necessary.

Researchers have used a variety of instrumentation to perturb the typical speech patterns of their participants, including random load-induced changes to articulators (Gracco & Abbs, 1985), pseudopalates (Aasland et al., 2006; Honda, Fukino, & Kaburagi, 2002), and bite blocks (Flege et al., 1988; Gay, Lindblom, & Lubker, 1981). These instruments have allowed speech scientists to examine how quickly and how completely individuals are able to adapt to speech perturbation, ultimately enabling them to better understand the flexibility inherent in the human speech production system.

Load-induced perturbation. Load-induced changes perturb the speech system by randomly applying a load to an articulator, such as the lips or the jaw, during an active speech task (Folkins & Zimmermann, 1982; Gracco & Abbs, 1985). This type of system enables speech scientists to examine both the immediate effects of perturbation and the immediate adaptations that are made to compensate for that perturbation. The other forms of perturbation commonly used (i.e., pseudopalates and bite blocks) better enable speech scientists to examine speech adaptation to perturbation over time.

Pseudopalates. A pseudopalate is a custom-made device that is fitted over the upper teeth and the roof of the mouth. Studies using pseudopalates have involved palates ranging in thickness between 1 mm and 6 mm, and still other studies have been conducted using palates that can be altered in their thickness randomly during speech tasks (McAuliffe et al., 2007; McFarland et al., 1996; Honda et al., 2002). These studies have revealed many important features of speech adaptation, including the rate at which this adaptation occurs. Aasland et al. (2006) found that when speakers were allowed to practice speaking with a pseudopalate for an hour, they improved speech production both acoustically and perceptually. It has been suggested that a period of between 45 minutes and 3 hours is generally required for maximal adaptation to the palate (McAuliffe et al., 2007). The results of these studies indicate that speech adaptation occurs over time and that a point of maximal adaptation can be reached acoustically. It is important to note, however, that other than electropalatographic (EPG) data gathered from tongue-to-palate contact, neither of these studies examined the movements of the articulators during adaptation; thus, conclusions about how the acoustic adaptations were achieved kinematically (i.e., how the articulators moved) cannot be drawn.

Bite blocks. Bite blocks are placed between the molars during speech tasks to perturb the speech production system by holding the mandible in a fixed position. Studies examining speech adaptation to bite blocks have used bite blocks ranging in thickness from 2.5 mm to 22.5 mm (Fowler & Turvey, 1980; McFarland & Baum, 1995). Bite blocks have been found to alter both the acoustic and perceptual quality of vowels, fricatives, and consonants (Fowler & Turvey, 1980; Gay et al., 1981; MacFarland & Baum, 1995).

Many speech perturbation studies have used acoustic data to measure the speed and extent of speech adaptation, determining that adaptation occurs when acoustic data from a perturbed speech system begin to normalize toward acoustic data from an unperturbed speech system. While this form of speech evaluation provides extremely valuable information, the movement patterns which created that acoustic adaptation remain ambiguous due to motor equivalence, as discussed above. Furthermore, Brunner and Hoole (2012) found that when the speech systems of typically-speaking individuals were perturbed by an artificial palate, the motoric adaptation patterns of each individual differed from one another, providing evidence for motor equivalence in perturbed speech systems in addition to typical, unperturbed speech systems. Thus, when studies use acoustic information to determine the extent of speech adaptation, that information only provides data regarding the extent of acoustic adaptation, but it provides no conclusive information regarding kinematic adaptation, or how the speakers' articulatory movements adapted to the perturbation.

While acoustic measures and analyses of speech are valuable, they do not provide any information concerning how articulatory movements adapt to perturbation. Studying speech adaptation to perturbation at a kinematic level will provide information about the flexibility inherent in the typical speaker's speech system that has not yet been studied in depth.

/s/ Perturbation Studies

As previously discussed, production of the /s/ phoneme requires great precision; therefore, it is very likely to be affected when an individual's typical speaking patterns are perturbed, making /s/ an ideal target to examine when studying adaptation to speech perturbation.

Aasland et al. (2006) examined the impact of a pseudopalate on tongue positioning for production of /s/ and found that (a) acoustically, the mean centroid frequencies of /s/ were much lower when perturbed and that (b) perceptually, /s/ production in the perturbed state never completely adapted to the pre-perturbation condition. Results of this study also revealed that participants' pseudopalate production of /s/ improved over the course of a one-hour practice period, indicating that speech adaptation to perturbation occurs over time, a finding replicated by Dromey et al., (2018). Rather than using a pseudopalate, Dromey et al. perturbed the speech of research participants by attaching electromagnetic sensor coils to their tongue, lips, and jaw, and subsequently measured their speech adaption over time using acoustic and perceptual measures. Dromey and colleagues found that participants' production of /s/ improved over time, with maximal adaptation occurring at approximately 10 minutes following sensor attachment. Flege et al. (1988) used bite blocks to perturb research participants' typical /s/ production and took data on the participants' linguapalatal contact patterns to provide further evidence supporting the hypothesis that speech adaptation to perturbation occurs over time.

Each of these studies examined the production of /s/ in a perturbed speaking state, and each study provided evidence for the occurrence of speech adaptation over time using acoustic, perceptual, and in the case of Flege et al. (1988), linguapalatal contact data. While these forms of data have provided important findings, they do not yield a complete picture. As previously noted, it is impossible to draw conclusions regarding the movement of a person's articulators based solely on acoustic and perceptual data due to motor equivalence. Flege et al. did use linguapalatal contact patterns, and while these contact patterns provide information regarding tongue placement, they do not provide any data regarding the movements of the lips or jaw, nor do they provide any information as to the movements of the tongue beyond palatal contact. Speech adaptation is complicated, particularly with the /s/ phoneme, and requires precise articulatory movements of both the tongue and the jaw, which have not yet been studied in detail. In order to obtain a comprehensive understanding of speech adaptation to perturbation, articulatory movements (not just their acoustic and/or perceptual corelates) must be examined.

Aims of the Study

This study will examine kinematic speech adaptation to a bite block over time, focusing specifically on the movements from the midpoint of an /aɪ/ diphthong through production of the /s/ phoneme within a phrase. Acoustic analysis of the first four spectral moments will also be performed to provide further insight into the relationship between kinematic and acoustic changes. We seek to supplement the findings of previous research which considered only acoustic and perceptual data when studying speech adaptation of the /s/ phoneme to perturbation. This study has been designed to gain an understanding of the kinematic processes that underlie the previously studied acoustic and perceptual speech adaptation to better understand how the brain compensates for that perturbation, as well as how that compensation occurs over time.

We hypothesize that when speakers experience bite block perturbation, their articulatory movements will initially undergo significant change, but will gradually adapt to the perturbation over time. We do not expect the speakers' movement patterns to return to their pre-perturbation state, but we do expect to see a significant change occur over the course of the adaptation period. Furthermore, we expect the deviation in articulatory movement to be reflected in the spectral moments of /s/, likely in an initial decrease of spectral mean and a gradual increase leading toward pre-perturbation levels as adaptation occurs.

Method

Participants

Participants in this study included eight males and seven females with typical language, speech, and hearing. They were recruited by word of mouth, and each signed a consent form approved by the Brigham Young University Institutional Review Board. The mean age of male participants was 25.4 with a standard deviation of 2.1 years, and the mean age of female participants was 24.3 with a standard deviation of 1.2 years. Each participant received $10 in compensation for their time.

Instrumentation

During recordings, each participant was seated 30 cm from a condenser microphone (AKG C20000B) in a single-walled sound booth. Articulatory movements were recorded using an NDI Wave electromagnetic articulograph (Northern Digital Inc., Waterloo, Ontario, Canada). Sensor coils were attached at the midline of the following six structures: tongue back (TB), tongue mid (TM), tongue front (TF), the vermillion border of the lower lip (LL), the vermillion border of the upper lip (UL), and the mandibular central incisors (J) to measure jaw movement. In addition, two reference sensors were glued to eyeglasses frames (without lenses) to correct for head movements and to serve as the origin of a coordinate system used to measure articulatory movement. Each coil was attached using cyanoacrylate adhesive except for Sensor J, which was attached to a small square of Stomahesive placed on the incisors (to protect the enamel of the teeth). The sensor coils tracked the x, y, and z positions of each articulator which were recorded on a computer located outside the sound booth using the Wavefront system. The audio signal was recorded at a sampling rate of 22050 Hz, and kinematic data were gathered at a rate of 100 Hz.

Bite blocks were created using Express dental putty (a silicone impression material) and were created between the molars bilaterally. The bite blocks were designed to form an inter-incisal gap of 10 mm for each participant. Tongue depressors were cut into 10 mm pieces and placed between the incisors of each participant to ensure that they held the correct position until the putty cured.

Speech Stimuli

This study examined the movements of the articulators from the starting point of the /aɪ/ diphthong to the production of /s/, in the phrase *I say*. The targeted sounds were produced in one of four sentences that were repeated as part of a larger set: (a) *I say ahree /əri/,* (b) *I say ahrae /əræ/,* (c) *I say ahroo /əru/,* and (d) *I say ahraw /əra/.* The focus of the present analysis is on the fourth stimulus sentence. Participants were instructed to say each sentence in one breath and to take a breath between each sentence. Speech tasks were modeled by an experimenter prior to participant production.

Procedure

Speech stimuli were produced prior to sensor attachment to obtain acoustic recordings of typical speech. Subsequently, an intensity calibration recording was made using a sound level meter (Extech 407736) with the participant saying /ɑ/ for five seconds. Calibration recordings were used as reference levels for subsequent speech recordings, which were made immediately post-sensor attachment, at two minutes post-attachment, four minutes post-attachment, and six minutes post-attachment. Between recordings, participants engaged in continuous conversation to facilitate adaptation to the sensors. After the recording was made at six minutes post-sensor attachment, the bite block was introduced. Speech stimuli were recorded immediately post bite block insertion and then at two-minute intervals during the following six minutes. Participants again engaged in conversation between recordings to facilitate adaptation. Following the recording made at six minutes post bite block insertion, the bite blocks were removed, and speech stimuli were produced one final time (with sensors still attached) to observe the process of decompensation to the bite block.

The present study focused on the recordings made directly before bite block insertion, immediately after bite block insertion, and at each two-minute interval within the six-minute timeframe to analyze adaptation to the bite block over time.

Kinematic Analysis

A custom Matlab application was created and used to segment longer recordings into individual sentence productions. Another Matlab application was used to further segment the sentence recordings to analyze the /aɪs/ VC syllable. During measurement with the Matlab applications, all of the stimuli were visually and auditorily inspected by the researcher to ensure accuracy of segmentation. The movements of the jaw, tongue, and lips were measured to analyze adaptation to the bite block over the course of six minutes. Measures of displacement (distance moved), peak velocity (maximum speed of movement), jaw contribution (amount that movements of the jaw contributed to the movements of other articulators) were obtained and analyzed for each recording.

Acoustic Analysis

The acoustic signal was visually and auditorily inspected to segment the production of each /s/ phoneme using Praat version 6.0.43 (Boersma & Weenink, 2020). The /s/ productions were then further segmented using a custom Matlab application, programmed to extract the central 50% of the phoneme. The first four spectral moments of those segmented /s/ productions were calculated with a script in Praat.

Statistical Analysis

A univariate repeated measures analysis of variance (ANOVA) was performed on the kinematic data, with the independent variables of (a) timeframe and (b) speaker gender and the dependent variables of (a) displacement, (b) peak velocity, and (c) jaw contribution, for each sensor placement. Each time measurement (i.e., two-minutes post bite block insertion [BB2], four-minutes post bite block insertion [BB4], six-minutes post bite block insertion [BB6], immediately post bite block removal [PostBB], and immediately prior to bite block insertion [PreBB]) was compared against the measure taken directly post bite block insertion (BB0) to reveal how speakers' articulators adapted in response to the bite block over time. An ANOVA was also performed on the acoustic data to determine the effect of (a) timeframe and (b) speaker gender on the mean of the four spectral moments of /s/: (a) mean, (b) standard deviation, (c) skewness, and (d) kurtosis. The significance level for all analyses was $p < 0.05$.

Results

Kinematic

The kinematic results described below will report the significant changes within individuals over time and any overall differences between men and women – that is, between-subjects effects for gender (see Tables 1 and 2). Contrast analyses evaluated differences between the BB0 time-point and the other recordings. The purpose in selecting BB0 as the "baseline" condition was to allow the examination of effects due to adaptation at the two, four, and six-minute points. It was anticipated that there would be substantial changes once the bite block was initially inserted and after its removal beyond the six-minute recording. These differences are reflected in the PreBB and PostBB recordings compared to the BB0 time.

Displacement (mm). A significant main effect for time was observed across recordings for the jaw, lower lip, and upper lip. For the jaw and the lower lip, the contrast analyses revealed higher displacement values at PreBB, BB4, and PostBB recordings, and for the upper lip higher displacement values were noted at PostBB as compared to displacement values measured at BB0. A between-subjects effect for speaker gender was also observed for the lower lip, with values being higher for females than males. It is noted that no main effect for time was observed for the tongue front, tongue mid, or tongue back, with displacement values remaining fairly stable across time recordings (see Figure 1).

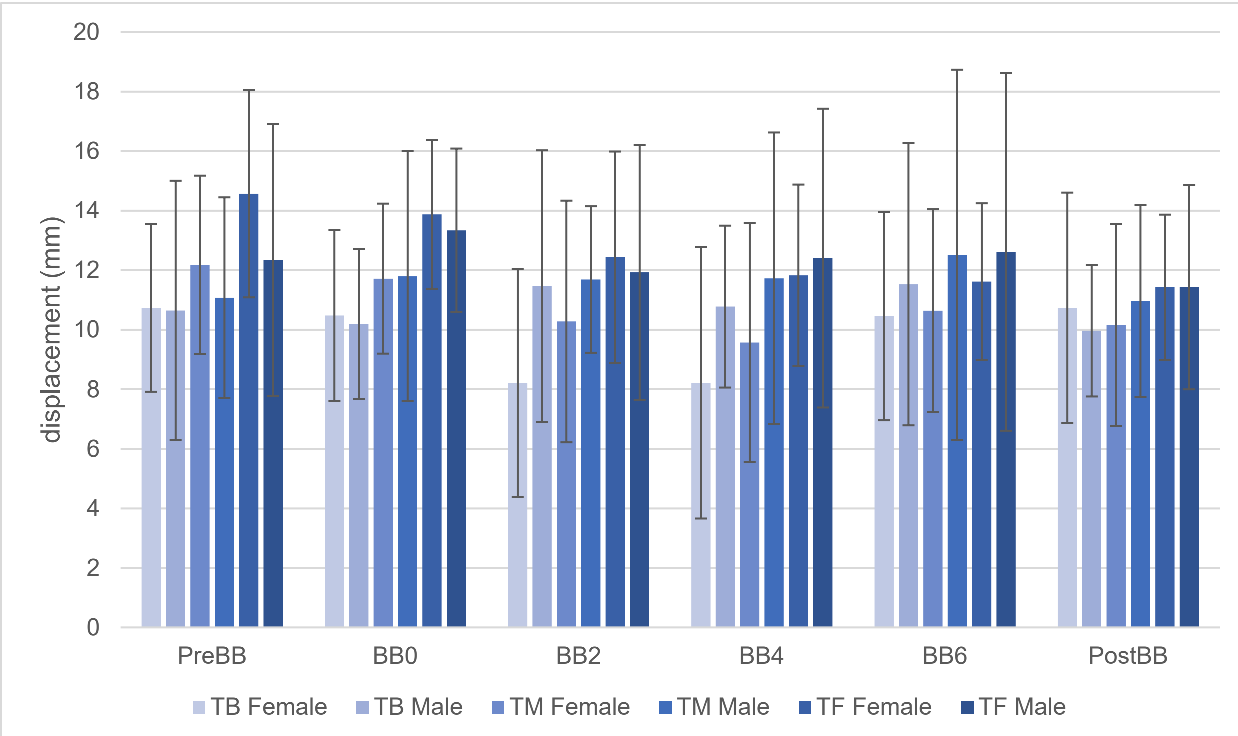

Figure 1. Mean (and standard deviation) of tongue (back, mid, and front) displacement before, during, and after bite block insertion.

Maximum velocity (mm/s). A main effect for time was observed across the recording intervals for the tongue back, tongue mid, jaw, and lower lip. Contrasts were significant for tongue back and tongue mid at PreBB, BB4, and PostBB recordings. The maximum velocity values of the tongue back initially decreased post bite block insertion (BB0), then increased at BB2, again at BB4, and then decreased slightly at BB6 prior to bite block removal (see Figure 2). A similar pattern was noted for the tongue mid velocity values and for male speakers' tongue front velocity values. Tongue front values for female speakers, however, demonstrated a different pattern, with maximum velocity levels increasing at BB0 when compared to PreBB values. At BB2, the values decreased toward PreBB levels and then increased again toward BB0 values where they remained until after bite block removal (PostBB).

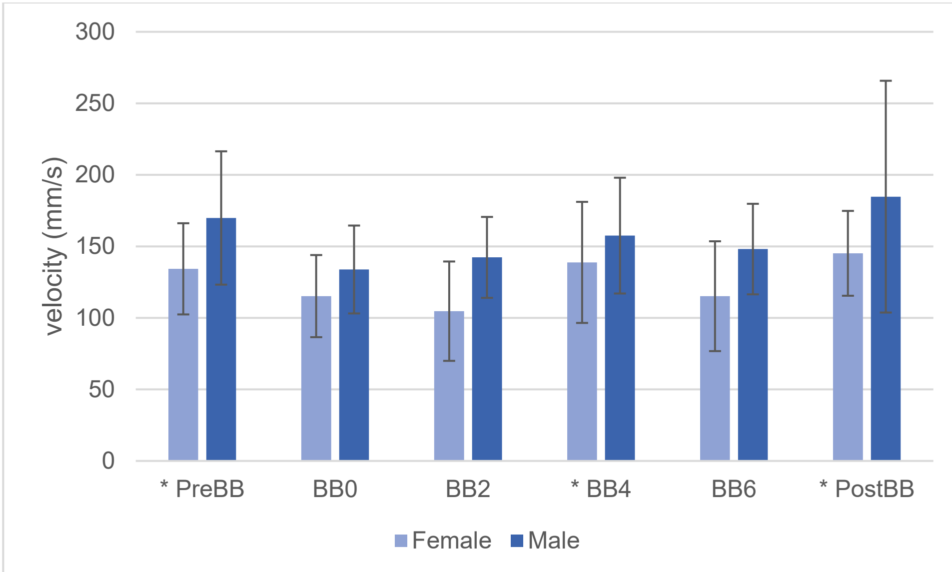

Figure 2. Mean (and standard deviation) of tongue back maximum velocity in millimeters per second for all speakers before, during, and after bite block insertion. The asterisks indicate a significant difference from the post-insertion (BB0) recording.

Significant contrasts for maximum velocity were also observed for the jaw at the PreBB recording and for the lower lip at PreBB, BB2, BB4, BB6, and PostBB recordings. Maximum velocity values for the lower lip of female speakers increased gradually from BB0 to BB2 to BB4, at which point values surpassed PreBB levels, and then decreased slightly at BB6 prior to bite block removal.

Jaw contribution (mm). A main effect for time was observed across recordings for tongue back, tongue mid, tongue front, and lower lip, with significant contrasts observed for PreBB, BB4, and PostBB recordings, all of which had values higher than those measured at BB0. A between-subjects effect for speaker gender was also observed for tongue back, tongue mid, and tongue front, with higher values for female speakers than male speakers.

Table 1

ANOVA Main Effects for Time and Between-Subjects Effects for Gender for the Kinematic Measures

	Time Effect				Gender Effect		
	df	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*
J dis	2.75, 35.77	72.41	< 0.001	0.85			
LL dis	4.23, 55.01	13.89	< 0.001	0.52	6.28	0.03	0.33
UL dis	5.00, 65.00	2.74	0.03	0.17			
TB max	3.36, 43.66	5.70	0.00	0.31			
TM max	5.00, 65.00	4.92	0.00	0.28			
J max	1.69, 21.94	36.12	< 0.001	0.74			
LL max	3.72, 48.40	3.58	0.01	0.22			
TB jaw con	2.48, 2.48	52.52	< 0.001	0.80	6.75	0.02	0.34
TM jaw con	2.74, 35.64	62.17	< 0.001	0.83	6.78	0.02	0.34
TF jaw con	2.83, 36.79	67.25	< 0.001	0.84	4.80	0.05	0.27
LL jaw con	2.88, 13.00	78.55	< 0.001	0.86			

Note. TB = tongue back; TM = tongue mid; TF = tongue front; J = jaw; LL = lower lip; UL = upper lip; dis= displacement (mm); max = maximum velocity (mm/s); jaw con = jaw contribution to the movements of the other articulators (TB, TM, TF, and LL) (mm)

Table 2

Contrast Statistics for the Kinematic Variables Comparing Recording Times Against the BB0 Recording

	BB2			BB4			BB6			PostBB			PreBB		
	F	*p*	*ηp²*	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*
J dis				5.80	0.03	0.31				68.29	< 0.001	0.84	109.11	< 0.001	0.89
LL dis				17.53	0.03	0.31				17.53	0.00	0.57	38.55	< 0.001	0.75
UL dis										7.80	0.02	0.38			
TB max				5.28	0.04	0.29				9.37	0.01	0.42	7.58	0.02	0.37
TM max				5.19	0.04	0.29				9.92	0.01	0.43	5.70	0.03	0.30
TF max													5.29	0.04	0.29
J max										28.95	< 0.001	0.69	76.22	< 0.001	0.85
LL max	10.28	0.01	0.44	5.54	0.04	0.30	8.75	0.01	0.40	27.65	< 0.001	0.68	9.72	0.01	0.43
TB jaw con				6.96	0.02	0.35				50.56	< 0.001	0.80	96.70	< 0.001	0.88
TM jaw con				6.84	0.02	0.35				60.20	< 0.001	0.82	103.61	< 0.001	0.89
TF jaw con				6.58	0.02	0.34				65.41	< 0.001	0.83	107.72	< 0.001	0.89
J jaw con				5.80	0.03	0.31				68.29	< 0.001	0.84	109.11	< 0.001	0.89
LL jaw con				5.48	0.04	0.30				75.61	< 0.001	0.85	112.26	< 0.001	0.90

Note. TB = tongue back; TM = tongue mid; TF = tongue front; J = jaw; LL = lower lip; UL = upper lip; dis = displacement (mm); max = maximum velocity (mm/s); jaw con = jaw contribution to the movements of other articulators (i.e., TB, TM, TF, and LL) (mm)

Acoustic

The acoustic results described below will report the significant changes within individuals over time and any overall differences between men and women (see Tables 3 and 4).

Spectral mean (Hz). A main effect for time was observed across recordings**.** Significant contrasts were noted for PreBB, BB4, and PostBB recordings (see Figure 3). The mean values for spectral mean decreased significantly upon bite block insertion (BB0). Values then increased toward PreBB levels at BB2 and again at BB4, but then decreased slightly at BB6 prior to bite block removal.

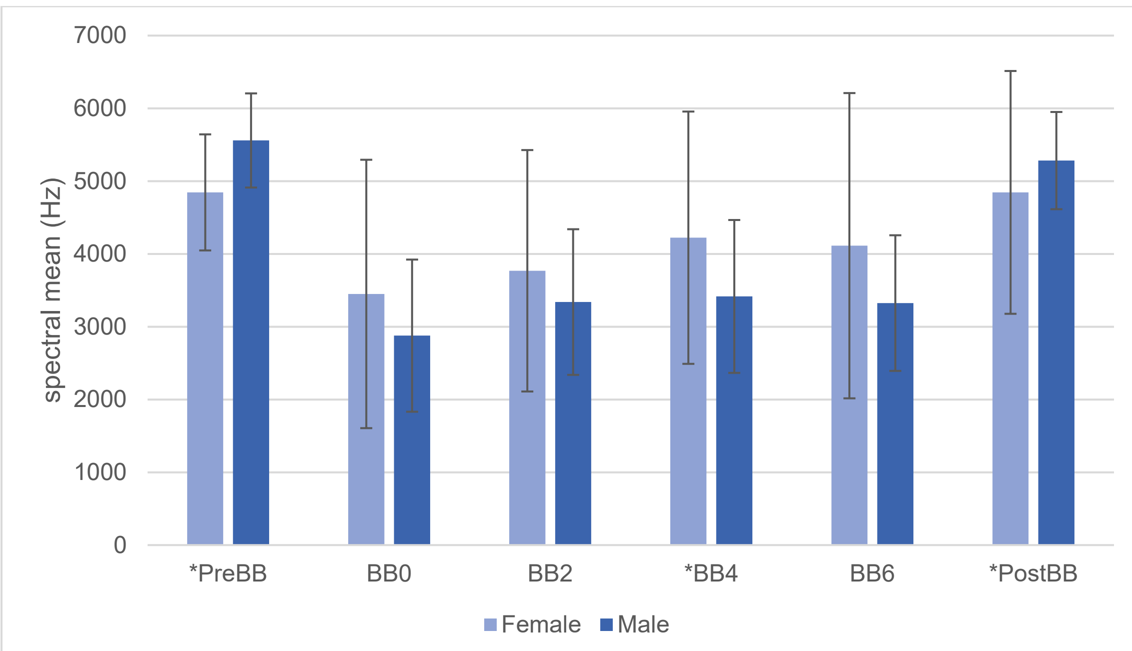

Figure 3. Mean (and standard deviation) of spectral mean in Hertz for all speakers before, during, and after bite block insertion. The asterisks indicate a significant difference from the post-insertion (BB0) recording.

Spectral skewness. A main effect for time was observed across recordings. Significant contrasts were noted for PreBB, BB4, BB6, and PostBB recordings. Mean values of skewness were significantly higher for both male and female speakers post bite block insertion (BB0) than they were PreBB (see Figure 4). Values decreased at BB2 and again at BB4 (though still below PreBB levels), then increased slightly at BB6 prior to bite block removal.

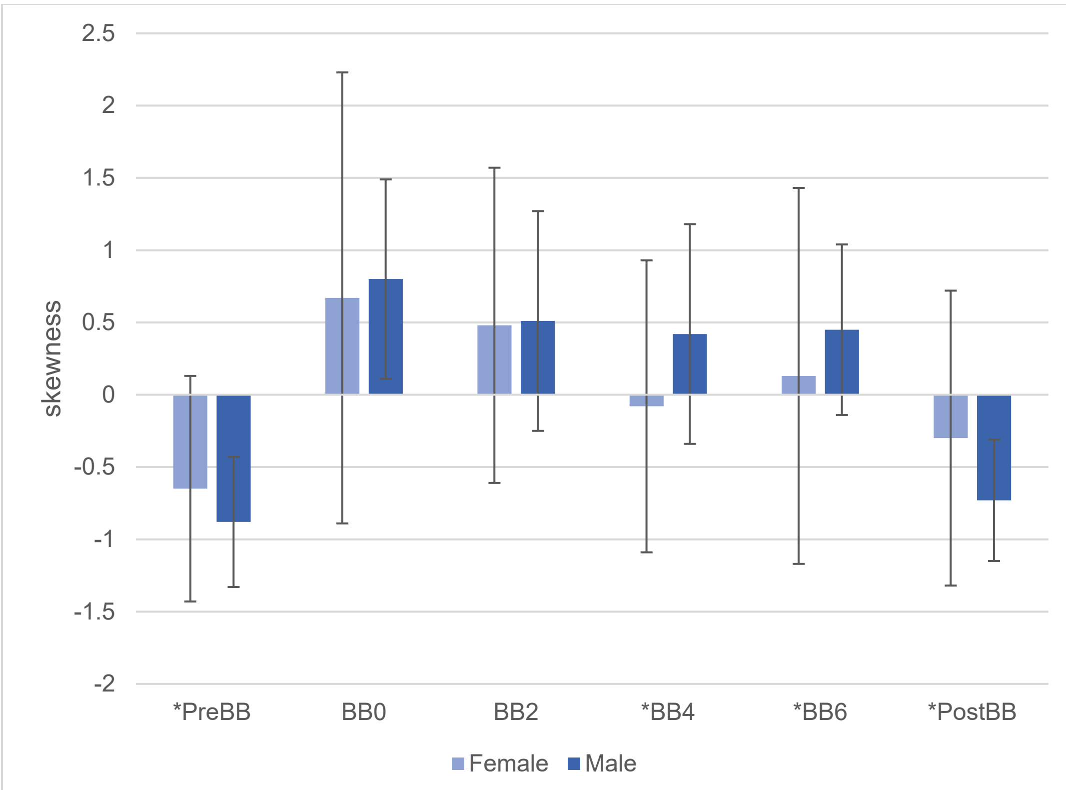

Figure 4. Mean (and standard deviation) of spectral skewness for all speakers before, during, and after bite block insertion. The asterisk indicates a significant difference from the post-insertion recording.

Between-subjects effects. A significant main effect for time was not observed for the mean of the spectral standard deviation; however, significant between-subjects effects for speaker gender were observed, with values higher for female speakers than for male speakers.

Table 3

ANOVA Main Effects for Time and Between-Subjects Effects for Gender for the Acoustic Measures

	Time Effect				Gender Effect		
	df	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*
Mean	3.68, 47.78	17.10	< 0.001	0.57			
SD					5.56	0.04	0.30
Skewness	4.17, 13.00	13.91	< 0.001	0.52			

Note. SD= standard deviation

Table 4

Contrast Statistics for the Acoustic Variables Comparing Recording Times Against the BB0 Recording

	BB4			BB6			PostBB			PreBB		
	F	*p*	*ηp²*	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*	*F*	*p*	*ηp²*
Mean	7.03	0.02	0.35				20.87	0.001	0.62	39.10	< 0.001	0.75
Skewness	6.53	0.02	0.33	5.46	0.04	0.30	15.55	0.002	0.55	34.59	< 0.001	0.73

Discussion

This study examined speakers' kinematic and acoustic adaptation to a bite block over time. Significant kinematic and acoustic effects were observed as speakers altered their articulatory patterns to compensate for the bite block.

Kinematic Compensation

No main effect for time was observed for the displacement of the tongue back, mid, or front. In other words, when the bite block was inserted, the tongue was still able to move the same distance that it had before the bite block was inserted. We expected to see a significant change in tongue displacement, particularly at the tongue back, as a result of its posterior attachment. However, levels of tongue displacement remained relatively steady throughout the experiment.

As noted in the introduction, the /s/ phoneme must be produced with precise articulatory placement and is one of the least-variable phonemes; therefore, typical adult speakers (like those participating in this study) have had years of practicing exact articulatory placement for perceptually accurate /s/ production (Dromey & Sanders, 2009). In order to produce /s/ with a bite block in place, a large compensatory movement of the tongue was necessary to approach the alveolar ridge. If the tongue had not risen as much as it did, no fricative production, regardless of quality, would have been possible. Lifelong practice in positioning the tongue for typical /s/ production may have enabled speakers to execute this compensatory movement.

Acoustic Compensation

The acoustic results of the present study revealed that the first and third spectral moments of /s/ (mean and skewness) demonstrated (a) an initial, significant change as a result of bite block insertion, and (b) adaptation to the bite block over time (see Figures 3 and 4).

The spectral mean for /s/ production decreased significantly upon introduction of perturbation, consistent with the findings of previous research (Dromey et al., 2018; McFarland et al. 1996; McLeod & Searle, 2006). Spectral mean values were then observed to increase gradually over time, demonstrating adaptation (see Figure 3). In 2018, Dromey et al. examined acoustic adaptation to electromagnetic sensor coils over a 20-minute period but did not observe adaptation over time. Placement of electromagnetic sensor coils at the midline of the tongue was consistent between the current study and the study conducted by Dromey et al.; thus, the differences in findings are likely the result of compensatory movements made specifically in response to bite block perturbation rather than the sensor coils. These compensatory movements are discussed further in the following section.

Measures of spectral skewness were negative prior to bite block insertion, a finding consistent with previous research regarding skewness for /s/ production in typical speakers (Jongman, Wayland, & Wong, 2000; McFarland et al., 1996; Nittrouer, 1995). Immediately post-bite block insertion, however, measures of spectral skewness increased significantly (see Figure 4), a pattern also demonstrated in studies of palatal perturbation (McFarland et al., 1996). McFarland et al. (1996) hypothesized that the change was likely due to significant differences in "lingual articulatory configuration for /s/," which could be true for the present study (p. 1100). However, research regarding spectral skewness has been rather inconclusive. Consequently, its physiologic mechanisms remain unclear (Nissen & Fox, 2009). Following the initial increase immediately post bite block insertion, measures of skewness, like measures of mean, gradually normalized toward PreBB values, demonstrating adaptation over time.

Kinematic and Acoustic Results Considered Together

One of the most valuable aspects of this study is that it considers kinematic and acoustic data together, providing further insight into the relationship between the movements of the vocal tract and the sounds that they produce. The results of this study have shown that when the movements of the articulators are disrupted by bite block perturbation, the acoustic measures of the /s/ phoneme are affected. The observed acoustic changes are likely the result of changes in tongue shape due to the immobility of the jaw.

Despite the fact that kinematic values of tongue displacement remained steady upon bite block insertion, acoustic measures were significantly affected. These findings support the conclusion reached by Subtelny, Oya, and Subtelny (1972) that the movements of the mandible, not just the tongue, contribute significantly to a speaker's ability to produce an acoustically (and therefore perceptually) accurate /s/. Wilcox, Stephens, and Daniloff (1985) also examined the impact of mandibular placement on /s/ production and found that children who misarticulate the /s/ phoneme exhibit different mandibular positions during /s/ productions, each unique to a particular pattern of misarticulation. Mandibular positioning and movement contribute significantly to the movements of the tongue; therefore, it is likely that the tongue was affected as a result of mandibular immobilization. Our results show that the tongue was not affected in terms of displacement, but it may have been affected in terms of shape.

As noted in the introduction, acoustically typical /s/ phonemes are produced by creating a narrow groove in the tongue. This groove may have been compromised as a result of bite block perturbation, because the tongue was required to move an increased distance to achieve PreBB levels of displacement without the contribution of the jaw. The current study was unable to provide data regarding changes in the shape of the tongue, but Flege et al. (1988) used palatometric data to study linguapalatal contact in bite block perturbation and found differences in the width of the tongue groove for the production of /s/ in response to the bite block. Therefore, it is likely that the narrow groove required for proper /s/ production was also compromised for speakers in the current study, resulting in acoustically atypical /s/ productions despite equivalent tongue displacement values. Given the observed adaptation over time, it is likely that speakers were able to normalize the shape of the tongue with practice, resulting in more acoustically typical /s/ productions.

Limitations of the Current Study and Implications for Future Research

The current study did not monitor tongue shape or positioning in response to bite block perturbation. Therefore, we cannot determine precisely which movements caused the acoustic changes observed. A future study could examine the relationship between mandibular positioning and tongue shape/positioning to provide further insight into the tongue's ability to compensate for bite block perturbation and the acoustic correlates of that compensation.

A second limitation to the current study is that the adaptation period observed was only six minutes; thus, we can only hypothesize whether adaptation would have continued to occur, had we allowed speakers to adapt to the bite block over a more extended timeframe. In order to further analyze the presence/pattern of adaptation over time, a future study could use the timeframe of 15 minutes used by McFarland and Baum (1995) (increasing from the present study's timeframe of six minutes), while taking spectral measurements frequently to more fully understand the pattern of acoustic adaptation which occurs over time.

A third and unexpected limitation to the study occurred as a result of speakers' inconsistency in biting down on the bite block. In theory, jaw movement should have remained steady through time measurements BB0, BB2, BB4, and BB6 due to bite block insertion; however, due to speakers' inconsistency; slight movements of the jaw occurred throughout the experiment, particularly at BB4. These movements may have contributed slightly to the adaptations observed during the study. In future studies, this limitation could be eliminated by providing participants with more explicit instructions to eliminate all jaw movements from occurring during speech production tasks by biting down on the bite block with adequate force.

Conclusion

The current study examined kinematic and acoustic adaptation to a bite block over time. We predicted that, following an initial change in kinematic and acoustic values upon bite block insertion, speakers would demonstrate gradual adaptation to the perturbation across the six-minute timeframe. Kinematically, we found that values of tongue displacement remained steady despite bite block perturbation. Acoustically, however, we found that significant changes were observed for spectral mean and skewness upon bite block insertion despite the unchanged measures of tongue displacement. These changes were likely caused by an alteration in tongue shape caused by mandibular immobilization. Thus, we have shown (1) evidence of the tongue's ability to move independently of the jaw (resulting, however, in potential shape changes) and (2) evidence of acoustic adaptation to a bite block over time. We have also demonstrated the value of considering kinematic and acoustic data together to gain deeper insight into the complex process of speech adaptation to perturbation.

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APPENDIX A

Annotated Bibliography

Aasland, W. A., Baum, S. R., & McFarland, D. H. (2006). Electropalatographic, acoustic, and perceptual data on adaptation to a palatal perturbation. *The Journal of the Acoustical Society of America, 119*, 2372-2381. https://doi.org/10.1121/1.2173520

Objective: The purpose of this study was to assess the impact of a perturbation on compensatory tongue positioning for production of the fricative /s/. *Methods:* Nine adult (19-27 years) native speakers of English served as participants. None of the participants had a history of communication disorders or prior experience wearing a dental appliance. Two EPG palates were constructed for each participant – one "normal" palate, about 1 mm thick with an array of 62 electrodes, and one "perturbed" EPT palate having a thickness of 6 mm at the alveolar ridge, maintaining the same spatial distribution of electrodes. Speakers produced multiple repetitions of the bisyllable /asa/ under three conditions: 1) no palate, 2) normal palate, 3) and perturbed palate at five time intervals. Speakers produced a total of twenty repetitions under each condition for baseline data. After collecting baseline recordings, stimuli were elicited from speakers every 15 minutes for a period of one hour, during which speakers read /s/-laden passages while wearing the perturbed palate. At each 15-minute interval, subjects would produce two blocks of ten repetitions of /asa/ while wearing the perturbed palate, alternating with two blocks of ten repetitions while wearing the normal palate. For the final time interval, an additional two blocks of ten repetitions of /asa/ were elicited with no palate in place to analyze any aftereffects of the palatal modification. Stimuli were recorded onto a computer using the Articulate Assistant software, and electropalatographic, acoustic, and perceptual analyses were analyzed for compensatory tongue positioning and compared to tongue positioning in nonperturbed conditions. *Results*: Production of /asa/ while wearing the perturbed palate improved over the course of the one-hour practice period. Acoustic data showed that mean centroid frequencies were much lower in the perturbed palate condition (as compared with the other two conditions), but that after the 60-minute practice period, no significant differences were found between the thick and no-palate conditions in /s/ centroid values. EPG data showed an increase in overall contact as well as an increase in medial and posterior contact for speakers with the thick palate in place. EPG data did not, however, show significant change over time. Negative aftereffects were observed in normal-palate productions. Perceptual analyses indicated that quality ratings were significantly higher in the no-palate condition than in the normal palate and perturbed palate conditions. *Conclusions*: Data from this study revealed evidence of the development of compensatory articulatory programs after a short, intense target-specific practice. This may indicate a sensorimotor recalibration and the development of novel speech motor programming appropriate for the change in oral form and function, which interpretation is supported by the negative after effects observed in the nonperturbed productions. *Relevance to Current Work*: This study examined the adaptation of articulatory movements to perturbation over time.

Ackermann, H., Hertrich, I., Daum, I., Scharf, G., & Spieker, S. (1997). Kinematic analysis of articulatory movements in central motor disorders. *Movement Disorders 12*, 1019-1027. https://doi.org/10.1002/mds.870120628

Objective: The purpose of this study was to examine and compare the lower lip trajectories of subjects with disorders of the corticobulbar tracts, cerebellum, and basal ganglia. *Methods:* 52 subjects participated in the study, coming from five different groups: (1) twelve patients suffering from an idiopathic parkinsonian syndrome (PD), (2) ten subjects with Huntington's disease (HD), (3) eleven patients suffering from an ataxic syndrome due to cerebellar atrophy (CA), (4) three patients with spastic dysarthria due to pseudobulbar palsy (PB), (5) and sixteen typical speakers who had never suffered from diseases of the brain or the cranial nerves (for baseline data). Eight different target words of the type "gepVpe" (V = a, i, y, u) were presented eight times in quasi-randomized order, and the subjects were asked to produce the presented target word in the phrase "Ich habe . . . gelesen" ("I have read . . ."). This was done eight different times to get a total of 64 utterances from each individual. To reduce the amount of data, the study considered only the utterance "Ich habe gepape gelesen" (short vowel /a/) for kinematic analysis. Kinematic analysis was done with an optoelectric movement analysis system, and the amplitude of the opening and closing gestures for "pap" was determined using a peak-picking algorithm developed by the Motor Control Lab of the Department of Neurology, Tübingen, Germany. This algorithm determined the amplitude and duration of both the opening and closing gesture in "pap". In addition to recording kinematic data from lip movements, speech was also recorded acoustically using a DAT recorder and a head-mounted microphone. To obtain an estimate of perceived speech motor deficits, an SLP evaluated the patient recordings and those of the controls. The evaluating SLP was asked to write down the perceived target word out of the eight different items randomly played. For each speaker the relative number of misassignments was calculated. *Results:* Patients with CA and PB exhibited slowed movement execution and an overall "stiffness," with a reduced ratio of peak velocity to maximum amplitude. The patients with PD had unimpaired velocity-displacement relationships, and the patients with HD showed significant bradykinesia under increased temporal demands (except for a single patient suffering from the akinetic-rigid Westphal variant of the disease). *Conclusions:* Execution of articulatory lip gestures does not seem representative of a common deficit of central motor disorders. *Relevance to Current Work:* This study used kinematic data and analysis to examine and compare speech movements.

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

Objective: The purpose of this study was to examine the effects of speaking rate on velocity profiles of lower lip and tongue tip movements during the production of stop consonants. *Method:* Five individuals with typical speech and hearing participated in the study. Participants produced the phrase *tap a tad above* 10 times at five different speaking rates. – conversational speaking rate, a rate four times faster than the conversational speaking rate, a rate two times faster than the conversational speaking rate, a rate half the speed of the conversational speaking rate, and a rate one quarter the speed of the conversational speaking rate. The speakers' lower lip and tongue tip movements were recorded using the University of Wisconsin x-ray microbeam system. Acoustic data were collected using a Shure SM81 microphone at a sampling rate of 20 kHz. *Results:* Changes in rate were associated with changes in the velocity profile, changing it from a single-peaked, symmetrical function when participants were speaking at a fast rate, to a multi-peaked, asymmetrical function when participants were speaking at a slow rate. *Conclusions:* The results support the theory that changes in speaking rate are associated with changes in motor control. Fast speaking rates appear to involve preprogrammed unitary movements, but slow speaking rates appear to utilize multiple, feedback-influenced submovements. *Relevance to the current work:* This study used speech kinematics to examine speech motor control.

Borden, G. J., & Gay, T. (1978). On the production of low tongue tip /s/: A case report. *Journal of Communication Disorders*, *11*, 425–431. https://doi.org/10.1016/0021-9924(78)90035-7

Objective: The aim of this study was to examine the nature (passive or active) of the tongue tip in speakers who produce /s/ in a tongue-tip down position. *Methods*: A native speaker of American English, who produces /s/ in a tongue-tip down posture participated in this study. To track muscle activity, hooked-wire electrodes were inserted into the genioglossus, the superior longitudinal, and the inferior longitudinal muscles. Electrodes were also inserted into the superior orbicularis oris for reference. Lead pellets were attached to the tongue tip and the tongue dorsum and were tracked using a 16-mm cine camera, which recorded X-ray film at a rate of 60 frames per second. Barium sulphate paste was placed on tongue dorsum, in addition to pellets, to add contrast. X-ray films were analyzed by hand tracings or each frame using a Perceptoscope Film Analyzer. EMG data were taken simultaneously with X-ray data, and EMG plots for each muscle were compared with X-ray data. *Results*: X-ray data revealed that for each production of /s/, the speaker's tongue tip was behind the lower incisors with the tongue dorsum bunched at the alveolar ridge. The elevation of the tongue tip never varied more than 3 mm during /s/ productions. EMG data revealed that the inferior longitudinal muscle (responsible for tongue tip depression) was active, above 200 μV, for each production of /s/. This data revealed that the tongue tip-down gesture was produced by active muscle movement, rather than passively being left at rest as the blade elevates to form the constriction. *Conclusions*: Tongue tip-up and tongue tip-down /s/ productions are both performed by active movements of the tongue, and in both cases, the proper constriction can be formed. Teaching individuals to use tongue tip-down lingual postures may therefore be beneficial in speech therapy. *Relevance to the current work*: This study examined a typical variation for /s/ production using kinematic data.

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

Objective: This purpose of this study was to investigate motor equivalence in the production of the German sibilant /ʃ/ under perturbation. After two weeks of adaptation to an artificial palate, researchers examined whether or not speakers would covary horizontal lip and tongue position, whether tactile landmarks have an influence on covariation, and to what extent speakers can foresee the acoustic result of the covariation. *Methods:* Six German speakers with typical speech, hearing, and occlusion participated in the study. Each speaker was fitted with a palate that either moved the alveolar ridge posteriorly ("alveolar palate") or made the palate flatter and lower by filling out the palatal arch ("central palate"). Speakers wore their prostheses between 12-18 hours a day over the course of two weeks, and they were instructed to read aloud an exercise sheet once a day to practice their speaking. The speakers were recorded in 6 sessions over the course of the two-week period. During each session, each participant produced the nonsense word /’ʃaxa/ in a carrier phrase (*Ich sah Schacha an*), randomized with 10 other CVCV sequences, each repeated 20 times in the same carrier phrase. This formatting elicited 120 repetitions of /’ʃaxa/ per speaker for the six sessions. Participants’ articulatory movements were recorded using electromagnetic articulography with sensors placed on the tongue, jaw, upper lip, bridge of the nose, and upper incisors. The utterances were also recorded acoustically and analyzed using Praat. *Results:* This study found that four speakers showed a covariation of lip and tongue movements in the production of /ʃ/. This study also found that acoustic output varies with tongue position, and that tactile landmarks do not play a large role in influencing speakers’ productions. *Conclusions: Relevance to Current Work:* This study showed kinematic and acoustic speech adaptation over time.

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. https://doi.org/10.1044/2017_jslhr-s-17-0169

Objective: The purpose of this study was to examine, using perceptual and acoustic measures, the time course of speech adaptation after the attachment of electromagnetic sensor coils to the tongue, lips, and jaw. *Methods:* Twenty native English speakers read aloud stimulus sentences before the attachment of the sensors, immediately after attachment, and again 5, 10, 15, and 20 minutes later. They read aloud continuously between recordings to encourage adaptation. Sentence recordings were perceptually evaluated by 20 native English listeners, who rated 150 stimuli (which included 31 samples that were repeated to assess rater reliability) using a visual analog scale with the end points labeled “precise” and “imprecise.” Acoustic analysis began by segmenting and measuring the duration of the fricatives /s/ and /ʃ / as well as the whole sentence. The spectral center of gravity and spectral standard deviation of the two fricatives were measured using Praat. These phonetic targets were selected because the standard placement of sensor coils on the lingual surface was anticipated to interfere with normal fricative production, causing them to become distorted. *Results:* Perceptual ratings revealed a decrease in speech precision after sensor attachment and evidence of adaptation over time; there was little perceptual change beyond the 10-min recording. The spectral center of gravity for /s/ decreased, and the spectral standard deviation for /ʃ / increased after sensor attachment, but the acoustic measures showed no evidence of adaptation over time. *Conclusions:* The findings suggest that 10 min may be sufficient time to allow speakers to adapt before experimental data collection with Northern Digital Instruments Wave electromagnetic sensors. *Relevance to Current Work:* This study examined speech compensation to perturbation over time.

Dromey, C., & Sanders, M. (2009). Intra-speaker variability in palatometric measures of consonant articulation. *Journal of Communication Disorders*, *42*, 397–407. https://doi.org/10.1016/j.jcomdis.2009.05.001

Objective: The aim of this study was to use electropalatometry to examine intra-speaker variability of linguapalatal contact. *Methods*: Twenty individuals produced VCV nonsense words following a 30-minute period in which participants engaged in conversation to adapt to their palatometers. Each nonsense word produced used a schwa in the initial position, followed by one of the 15 palatal consonants, and ended with one of the three corner vowels, /ɑ/, /i/, /u/. Recordings were made using a head-mounted condenser microphone (AKG C-420), and the LogoMetrix palatometer system recorded tongue-to-palate contact. Place, manner, voicing, and coarticulation were compared using a variability index to examine speaker consistency. *Results*: Significant differences, revealed by a repeated measures ANOVA, were found for manner of articulation in the /ɑ/ vowel context place of articulation in the /i/ vowel context. It was also found that test participants demonstrated differences in production variability across sounds (within individuals), and also demonstrated differences from one participant to another. It was also noted that production of /s/ was significantly less variable than /r/ in the /ɑ/ vowel context. *Conclusions*: This study found significant differences in phoneme production variability, associated with the manner, place, and vowel context. These findings provide a deeper understanding of what should be expected with regard to normal variability in phoneme production. *Relevance to Current Work*: This study examined normal variability for production of the /s/ phoneme.

Flege, J. E., Fletcher, S. G., & Homiedan, A. (1988). Compensating for a bite block in /s/ and /t/ production: Palatographic, acoustic, and perceptual data. *The Journal of the Acoustical Society of America, 83*, 212-228. https://doi.org/10.1177/0023830911434098

Objective: The purpose of this study was to determine which articulatory characteristics of /s/ and /t/ are critical and which are redundant by examining the linguapalatal contact patterns of individuals wearing a bite block. *Methods:* Five adult males, between 19 to 21-years-old with normal speech and hearing participated in the study. Three of them were monolingual Arabic speakers (A1, A2, A3) and two were monolingual English speakers. Each speaker wore a bite block, which increased interincisal distances by 8-15 mm) and an electropalatograph. The English /s/ and /t/ tokens were embedded in the phrase "Say to me—again." The Arabic /s/ and /t/ occurred in a carrier phrase translated "You asked me—more." Phonetically similar English words and Arabic words were randomly inserted into carrier phrases, and the subjects were unaware that /s/ and /t/ were to be analyzed. Four samples were taken: two normal speech (N1, N2) and two with the bite block (B1, B2). B1 was taken immediately after the bite block was inserted, and B2 was taken 10 minutes after it was inserted. Data were taken using the electropalatograph – the number of sensors (out of 96) contacted for each /s/ and /t/ token was calculated by software to display area of linguapalatal contact. Data were also analyzed acoustically and perceptually by a practiced listener using a scale ranging from "normal" to "distorted". *Results:* The analyses of the spectra associated with /s/ and /t/ revealed significant differences between bite block and normal speech samples. For /s/, fewer sensors were contacted in B1 than B2, and fewer sensors were contacted in B2 than the non-bite block samples. The groove width of the Arabic speakers' production was affected significantly, and the bite block caused some speakers to shift their tongue position posteriorly during production. For /t/, all three Arabic subjects contacted significantly fewer sensors in the bite block and normal speech samples. The two English subjects, however, contacted significantly more sensors in the bite block than normal speech samples. *Conclusions:* The area of tongue-palate contact increased as the constriction for /s/ moved forward in the mouth, and as constriction moved forward in the mouth for /t/, the number of sensors contacted increased. The one subject in five who frequently did not show a groove in the first bite block sample (B1) did so after 10 min of practice speaking with the bite block (in sample B2), indicating that the groove is essential for successful /s/ production. *Relevance to Current Work:* This study examines compensation for a bite block over time, using palatographic and acoustic data.

Folkins, J. W., & Zimmermann, G. N. (1982). Lip and jaw interaction during speech: Responses to perturbation of lower-lip movement prior to bilabial closure. *The Journal of the Acoustical Society of America*, *71*, 1225–1233. https://doi.org/10.1121/1.387771

Objective: The purpose of this study was to perturb lower-lip movement prior to bilabial closure and to observe: 1) whether a compensatory response occurred, 2) if it does, whether it is exclusively performed by the upper lip or whether the jaw is able to compensate as well, and 3) whether the characteristics of any compensatory response change relative to the timing of lip perturbation or to the jaw position at the onset of lip perturbation. *Methods*: Three typically-speaking young adults participated in the study. Each subject repeated the syllable /æp/ 150 to 200 times with a pause of 2 to 4 seconds between each repetition. Electrical stimulation of the depressor labii inferior muscle was used to produce unexpected, involuntary depression of the lower lip during non-subsequent repetitions. Lip depressions that occurred between 40-500 ms prior to voice offset were used in data analysis. Upper-lip, lower-lip, and jaw movements were transduced in the inferior-superior dimension with a strain gauge system. The data were analyzed by comparing each stimulated syllable with the normal syllable immediately preceding it. *Results:* “Both the jaw and upper lip compensated for the involuntary perturbations in lower-lip movement. Compensatory movements did not occur as additional, discrete gestures following stimulation onset, but appeared as an increase in the size of closing movements. Bilabial closure was produced at the typical time in 68% of the perturbed syllables, but it was delayed (a mean of 61 ms) in the remaining 32%. Neither the incidence nor the magnitude of this delay appeared to be related to the jaw position at stimulation onset or to the time between stimulation onset and voice offset. *Conclusion*: This study indicates that the upper lip and jaw can make compensatory movements to aid bilabial closure in the face of perturbation. *Relevance to current work*: This study analyzed compensatory articulatory movements.

Forrest, K., Weismer, G., Milenkovic, P., & Dougall, R. N. (1988). Statistical analysis of word-initial voiceless obstruents: Preliminary data. *The Journal of the Acoustical Society of America*, *84*, 115–123. https://doi.org/10.1121/1.396977

Objective: The purpose of this study was to describe a quantitative approach for classifying obstruent spectra. *Methods*: Five male speakers and five female speakers, aged 18-31, participated in the study. Speakers produced monosyllabic words with an initial voiceless obstruent six times in the carrier phrase “I can say _____, again”. Fast Fourier transforms (FFT) (using a 20-ms Hamming window) were calculated every 10 ms from the start of the obstruent to the following vowel. The first four spectral moments were computed from each FFT. Moments were calculated from linear and Bark transformed spectra, and data were grouped according to vowel contexts for speakers of each gender. *Results*: 92% of voiceless stops were classified accurately using the moments calculated from the linear spectra when dynamic aspects of the stop were considered. It was also found that the model of classification created from the males' data was able to correctly classify approximately 94% of the voiceless stops produced by the female speakers. *Conclusions:* The results indicate that a spectral moments can be used to quantitatively classify word-initial voiceless obstruents, even across gender. *Relevance to current work*: This study examined obstruent spectra using spectral moments.

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

Objective: The purpose of this study was to examine whether a bite block affects the latency and/or the quality of spoken vowels. *Method:* Two groups of subjects produced a set of vowels /i, ɛ, a, ɔ, ʌ, u/ without a bite block followed by the same set of vowels produced with a 14 mm bite block, clenched between the front teeth. One group produced responses under time pressure; the other did not. Two microphones were used – one to measure the millisecond counter and the other to record the warning bell and vocal response on tape for later acoustic analysis. Each subject underwent 36 practice trials, 90 trials without the bite block, and 90 trials with the bite block (divided into sets of 18). The vowels of each recording were subsequently analyzed for subjects' reaction time, acoustic accuracy, and perceptual quality. *Results:* The first six bite block vowels produced differed significantly in terms of acoustics from both the typically-produced vowels and the remaining bite block vowels, possibly indicating a rapid learning effect within the first set of 18 trials. The bite block vowels did not differ significantly in terms of latency and were perceived as being of slightly lesser quality than the normal vowels. *Conclusions:* There may be no way anatomically to compensate for some configurational changes made by the bite block. We are hampered in understanding these partial compensations, because we cannot determine what the structural possibilities are for full compensation. *Relevance to Current Work:* This study used acoustic and temporal data to track speech compensation to a bite block over time.

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. https://doi.org/10.1121/1.385591

Objective: The purpose of this study was to determine how speakers make articulatory compensations in producing acoustically normal bite block vowels. *Method:* Five adult males having normal speech and hearing produced /i/, /o/, and /u/ while wearing a 22.5-mm bite block, and a 2.5-mm bite block while producing /ɑ/. Each subject was seated in a dental chair with his head restrained in a standard x-ray holder so that x-rays could be taken of the entire vocal tract. Each subject produced each vowel (random-ordered) in a series of three triads (V-V-V, V-V-V, V-V-V), first without a bite block, and subsequently while wearing the bite block. They were instructed to attempt to match the quality of those vowels produced with the bite block to the quality of those vowels produced without. Data were taken through x-rays as well as an acoustic recording for all vowel productions. X-ray analysis was performed in two ways: (1) an analysis of the outline of the vocal tract from the lips to the vocal folds, (2) an analysis of vocal tract cross-dimensions, plotted by segment by a PDP-8 computer. Wideband spectrograms were also made for each of the utterances where x-rays were recorded. *Results:* Analysis of the x-ray films revealed that the subjects compensated for the bite blocks by attempting to match the original, non-bite block state. The data also demonstrate that they were often successful, because the vocal tract cross-dimensions were typically matched along the length of the vocal tract with minimum deviation (maximum compensation) occurring at or near the points of maximum constriction. Deviations were most often located at points of large vocal tract area. *Conclusions:* In bite block vowels with formant patterns close to normal, cavity shapes resembled those observed for normal productions. This indicates that speakers compensate for the bite block by using lip and tongue supershapes as hypothesized in previous work. The cross-sectional data revealed that compensatory adjustments were often partial except at points of maximum constriction. *Relevance to Current Work:* This study examined the movements of the oral cavity in subjects speaking with a bite block.

Gracco, V. L., & Abbs, J. H. (1985). Dynamic control of the perioral system during speech: Kinematic analyses of autogenic and nonautogenic sensorimotor processes. *Journal of Neurophysiology*, *54*, 418–432. https://doi.org/10.1152/jn.1985.54.2.418

Objective: The purpose of this study was to examine the kinematic adjustments of the upper and lower lips to load-induced changes. *Methods:* Five adult females between the ages of 25 and 35 years of age participated in this study. Afferent contributions to the motor control of their speech were evaluated by applying unanticipated loads to their lower lips during production of bilabial stops. These loads were introduced randomly in approximately 15% of trials, and a total of 490 load trials were distributed within a restricted interval (100 ms). These loads were centered on the initiation of agonist muscle contraction associated with the lip-closing movements. Kinematic adjustments of the upper and lower lips were monitored using the following measures: 1) time of load onset relative to initiation of contraction in the orbicularis oris inferior (inferior labial elevator); 2) extent of inferior labial displacement; 3) velocity of inferior labial displacement; and 4) peak displacement and peak velocity of both upper and lower lip movements for production of bilabial stop /b/. *Results*: In each subject, perturbation resulted in changes in upper and lower lip displacement, movement time, and closing velocity that were statistically significant and occurred the first time a load was introduced. The compensatory movement displacements in earlier-occurring loads were highly related to the magnitude of the perturbation displacement. One of the subjects displayed differences in movement velocity and movement time from the other four subjects, demonstrating nervous system flexibility. *Conclusions*: The results from this study suggest that afferent information is used to specify and update control parameters of motor programing before agonist muscle activation begins. After muscle activation begins, afferent input shapes the ongoing motor output, primarily through nonautogenic adjustments. *Relevance to the current work*: This study used kinematic analysis to examine compensatory upper and lower lip motor movements for speech.

Hardcastle, W. J., Gibbon, F. E., & Jones, W. (1991). Visual display of tongue-palate contact: Electropalatography in the assessment and remediation of speech disorders. *British Journal of Disorders of Communication, 26*, 41–74. https://doi.org/10.3109/13682829109011992

Objective: The aim of this article was to outline technical developments of the electropalatograph and describe techniques for utilizing electropalatography in assessment and treatment of speech disorders. *Results:* Using electropalatography, typical /s/ production was found to be produced using an "alveolar grooved pattern." In this contact pattern, the tongue made complete lateral contact with the palate bilaterally, but did not make contact with the central/anterior-most portion of the palate. This contact pattern, as the name indicates, forms a groove down the midline of the tongue for proper /s/ production. It was also found that when the central groove was wider than typical, the production of /s/ was perceived as atypical. *Conclusion*: When using electropalatography for treatment of a misarticulated /s/ phoneme, lingual placement is extremely important. When the alveolar grooved pattern is not correctly formed, production of the /s/ phoneme is distorted. *Relevance to the current work:* This article outlined proper lingual placement for typical /s/ production.

Hertrich, I., & Ackermann, H. (2000). Lip-jaw and tongue-jaw coordination during rate-controlled syllable repetitions. *The Journal of the Acoustical Society of America, 107*, 2236–2247. https://doi.org/10.1121/1.428504

Objective: The purpose of this study was to investigate the relationship between compound gestures and single-articulator movements of the jaw, the lower lip, and tongue tip during rate-controlled syllable repetitions. *Methods*: Nine subjects produced repetitions of the CV sequences /pa/, /pi/, /ta/, and /ti/ in two conditions, slow and fast. Three repetitions were elicited in the slow condition, and five were elicited in the fast condition by binaural presentation of synthetic syllables over headphones. The movements of speakers' articulators were measured using electromagnetic articulography at a sampling rate of 400 Hz. Receptors were placed on the speakers' upper lips, lower lips, upper jaw (above the upper incisors), lower jaw (below the lower incisors), tongue tip (0.5 cm behind the tip of the tongue), tongue dorsum (about 4 cm posterior to the tongue tip), and nasion by means of a tissue glue. In this study, only the lower lip, tongue tip, and lower jaw receivers were evaluated for the systematic influence of place of articulation (/p/, /t/), vowel type (/a/, /i/), and rate condition (slow - 3 Hz, fast - 5 Hz) on movement cycle amplitudes (mean of opening and closing amplitude). *Results*: The results revealed that jaw amplitude was closely linked to vowel height during bilabial articulation, and that lower lip amplitude was linked to production rate. An increase in rate was linked to an increase in velocity/amplitude for jaw movements, whereas the constrictors were not as rate sensitive; this negative covariation across repetition has been considered to be an indicator of motor equivalence. *Conclusions:* The assumption that single-articulator gestures directly correspond to basic phonological units is not supported by the findings of this study. The results of this study indicate that single structures are differentially affected by speech rate. *Relevance to the current work*: This study used kinematic data to analyze speech movements.

Honda, M., Fukino, A., & Kaburagi, T. (2002). Compensatory responses of articulators to unexpected perturbation of the palatal shape. *Journal of Phonetics*, *30*, 281–302. https://doi.org/10.1006/jpho.2002.0172

Objective: This study examined compensatory articulatory behavior in response to unexpected perturbation of the oral cavity. *Methods*: Two adult male speakers participated in the study. Each subject was fitted with an artificial palate with a thickness that was dynamically changed (between 2 and 5 mm) using a mechanical device that could inflate/deflate a balloon placed on the palate. The syllables /ʃa ʃa…. ʃa/ and /tʃat tʃa… tʃa/ were each uttered 8 times under each test condition, following the leading syllable /iya/. Four conditions were examined in the experiment: steady-state deflated, steady-state inflated, inflation (dynamic), and deflation (dynamic). Palatal perturbations were examined under normal and masked (88 dB pink noise) auditory-feedback conditions. The experiment was carried out in four sessions. The subject was allowed to practice for 5 minutes with the artificial palate deflated before the first session, and with it inflated before the third session. The results were examined with a perceptual test, conducted on the speech errors that occurred in the perturbed trials, for a total of 192 stimuli. The intended task of the perceptual test was to identify each consonant in the repeated syllable using any consonant category of Japanese, though the listener was allowed not to judge it as a phonemic category when the speech was not identified as a clear phonemic category. The data were also analyzed acoustically, using a low pass filter with a cutoff frequency of 8 kHz, six LPC-cepstral coefficients were obtained by a 12-pole LPS analysis. A multi-variate analysis of variance was performed on the six cepstral parameters of the acoustic segments for the initial and middle (fourth) syllable in the repeated syllables to test for significant differences between conditions. *Results*: The perceptual analysis revealed that effect of the artificial palate was different for each speaker. For the phoneme /ʃa/, subject A had a mean error identification score of 94%, and subject B had a mean error identification score of 72%. Subject A's /ʃa/ speech errors disappeared in the 2nd syllable, while subject B's speech errors didn't disappear until the third syllable. In the steady-state inflated condition, speech errors were frequent. The fricative /ʃ/ was most commonly misidentified as the affricate /tʃ/, while the affricate /tʃ/ was most commonly misidentified as the stop /t/. These errors occurred throughout all of the repeated syllables for many trials. Acoustic analysis revealed that when the /ʃ/ fricative was perceived as an affricate, it can be interpreted as an overshoot of the tongue relative to the modified palate shape, which causes vocal-tract closure that resulted in the lack of a fricative onset. This same overshoot was the common compensatory response to the affricate /tʃ/, though it was less noticeable. This rapid compensatory response was also observed in the masked condition, though the horizontal and vertical displacements of the repeated syllables were larger than in the unmasked condition. *Conclusions*: This study suggests that compensatory responses to palatal perturbation may be driven by tactile, not auditory information, as suggested by the common compensatory overshoot of the under both masked and unmasked conditions. This study also suggested that auditory feedback is used in ongoing speech production when adaptation to the structural perturbation is not sufficient. *Relevance to current work:* This study examined speech adaptation to perturbation over time.

Hughes, G. W., & Halle, M. (1956). Spectral properties of fricative consonants. *The Journal of the Acoustical Society of America, 28*, 303–310. https://doi.org/10.1121/1.1908271

Objective: The aim of this study was to examine and describe the spectral properties of the eight standard English fricative consonants: /f/, /s/, /ʃ/, /v/, /z/, /ʒ/, /θ/, /ð/. *Methods*: Two female and three male research participants were instructed to read a list of isolated words containing all fricatives in contexts before and after the major vowel classes. Words were recorded onto a single tape, and subsequently, isolated words were recorded onto tape loops from the master tape. 190 words were eventually analyzed. Energy density spectra were measured using a fixed band-width filter, with a range of 300-10,000 cps. The measured output was then squared and fed to a holding circuit and meter, where it was checked for transition accuracy and analyzed using a 20 msec and a 50 msec portion of a 2000 cps sine wave. The study design also incorporated perceptual measures. 200 samples of /s/, /f/, and /ʃ/ were presented to 10 listeners who were asked to identify which fricative was being presented to them. This process was repeated two times, with data from both sets of presentations being analyzed together. *Results*: For any single speaker, the spectra of /s/, and /z/ have peaks at higher frequencies than the other fricatives tested. It was found that /s/ and /f/ consistently had strong concentrations of energy in the range above 4 kc. These phonemes were different, however, in that /f/ contained significantly more low-frequency energy than did /s/, and /ʃ/ contained an even greater amount of low energy than /f/. In terms of perceptual measures, it was found that listeners frequently misidentified the /f/ phoneme for an /s/ phoneme for one speaker who produced /f/ with a higher-than-average amount of high-frequency energy. For another speaker, /s/ was often identified by listeners as being an /ʃ/, because that speaker produced /s/ with a higher-than-average amount of low-frequency energy. *Conclusions*: Producing an acoustically and perceptually typical /s/ fricative requires great precision and accuracy. If too much low-frequency noise is included in /s/ production, the /s/ will begin to take on both perceptual and acoustic characteristics of /ʃ/. *Relevance to the current work:* This study identified and described acoustic and perceptual characteristics of a typically-produced /s/ phoneme.

Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English fricatives. *The Journal of the Acoustical Society of America*, *108*, 1252–1263. https://doi.org/10.1121/1.1288413

Objective: The aim of this study was to analyze acoustic cues for classification of place of articulation in fricatives. *Method:* Twenty native American English speakers (ten male, ten female) with no history of speech or hearing impairments participated in the study. Participants produced the English fricatives in CVC contexts in the carrier phrase *Say* ___ again, repeating each syllable three times within the phrase. Speakers were recorded at 22kHz. For each recording, spectral peak locations were analyzed, spectral moment values were computed, locus equations were derived, root-mean-square amplitude was measured, and relative amplitude in dB was measured. Results*:* All four places of fricative articulation can be distinguished by spectral peak location, spectral moments (mean, standard deviation, skewness, and kurtosis), and both normalized and relative amplitude. *Conclusions:* Static and dynamic acoustic properties can provide information regarding all four places of articulation regardless of variation in voicing, speaker, and vowel context. *Relevance to the current work:* This article provides information regarding the acoustic properties of fricatives.

Lametti, D. R., Nasir, S. M., & Ostry, D. J. (2012). Sensory preference in speech production revealed by simultaneous alteration of auditory and somatosensory feedback. *The Journal of Neuroscience*, *32*, 9351–9358. https://doi.org/10.1523/JNEUROSCI.0404-12.2012

Objective: The purpose of this study was to determine the role of both auditory feedback and somatosensory feedback in the speech of healthy adults. *Methods*: Seventy-five native English speakers (between the ages 18-40) with normal speech and hearing participated in the study. Speakers were asked to repeat the word "head," which was displayed on a computer screen, at a comfortable pace until the word was removed from the computer screen, which averaged about 11 repetitions. Somatosensory feedback was perturbed during production using a small robotic device, which was attached to a dental appliance fitted to the lower jaw. The robot applied a load that pulled the mandible outward, perpendicular to the movement path. Males received an average peak force of 2.25 N, and females received an average peak force of 1.89 N. Auditory feedback was perturbed by changing the sound of speakers' voices in "near real-time." Using an acoustical effects processor and filters, F1 was shifted downward (leaving the other formants and fundamental frequency the same), mixed with 70 dB noise, and played back to the speakers via headphones. Fourteen speakers experienced the somatosensory perturbation alone, fourteen subjects experienced the auditory perturbation alone, fourteen subjects experienced both perturbations simultaneously, seventeen subjects experienced the auditory perturbation first, followed by both perturbations at the same time, and sixteen subjects experienced the somatosensory perturbation first, followed by both perturbations at the same time. The data were analyzed using kinematic and acoustic analysis. *Results*: All speakers compensated for at least one form of altered sensory feedback. There is an inverse relationship between reliance on auditory versus somatosensory feedback – the more speakers compensate for one, the less they compensate for the other. *Conclusions*: Speakers tend to have a preferential reliance on either auditory or somatosensory feedback during speech production. *Relevance to current work*: This study used kinematic analysis to study speech adaptation to perturbation.

McAuliffe, M. J., Robb, M. P., & Murdoch, B. E. (2007). Acoustic and perceptual analysis of speech adaptation to an artificial palate. *Journal of Clinical Linguistics and Phonetics*, *21*, 885-894. https://doi.org/10.1080/02699200701576827

Objective: The purpose of this study was to examine the process of speech adaptation to a standard electropalatographic practice palate. *Methods:* Eight adult females (undergraduate students of speech pathology) participated in the study. They all had normal dental occlusion, typical hearing, and no experience with orthodontic retainers. Twelve CVC words embedded within the carrier phrase "a CVC" were repeated five times under four speaking conditions. The word initial consonants included /t/, /k/, /s/, and /ʃ/, the vowels were /I/, /a/, and /u/, and the word final consonants were either /t/ or /p/. The CVC words were presented in random order across four conditions: (1) normal speech (without the palate), (2) immediately post-insertion of the palate, (3) 45 minutes following the insertion of the palate, and (4) 3 hours following insertion of the artificial palate. Each practice palate (containing no electrodes of lead wires) was approximately 1-2 mm thick and was molded to the individuals' hard palates. Subjects read a CVC phrase in each of the four conditions. Data were recorded using a head mounted microphone at a sampling rate of 44kHz with a Sony Digital Audio Tape recorder in a sound treated room. Perceptual analysis was performed on the third repetition of five produced by each participant under each condition. Each listener was asked to evaluate word-initial consonant precision of each CVC word using a sliding analog scale of 0 (normal precision) through 10 (severe imprecision). 25% of the perceptual sample was re-rated for intra-judge reliability. Acoustic analysis was done using Praat software to compare segment durations, first and second vowel formant frequencies, and consonant spectra. *Results:* A repeated measures analysis of variance test revealed a significant increase in consonant imprecision between the pre-palate condition and both the post and 45-minute conditions respectively. Consonant imprecision was found to reduce significantly from the post to 45-minute condition and the post to 3-hour condition. Spectral analysis results showed significant change across all conditions. *Conclusions:* Speech adaptation to an artificial palate takes place over time, and based on this study, a period of between 45 minutes and 3 hours is generally required for maximal adaptation to the palate. The imprecision resulting from an EPG palate is usually quite mild, and individuals adapt at different rates. *Relevance to the current work:* The study uses both acoustic and perceptual analysis to evaluate the process of speech adaptation over time. The study also focuses on the timeline of adaptation.

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

Objective: The purpose of this study was to examine the extent of compensation and the role of feedback in developing compensatory strategies after the introduction of a bite block. *Method*: Fifteen adult female native speakers of French (free from hearing and communication disorders) participated in the study. Participants were screened to ensure normal occlusal relationships. Measurements were made of the vowels [i a u], the fricatives [s ʃ] preceding the three vowels, and the stop consonants [p t k] also preceding the three vowels. Each stimulus was repeated ten times in random order in a series of perturbed and unperturbed conditions. Two subtests were run: immediate compensation and postconversation. The immediate compensation subtest included three conditions: (1) jaw-free or normal, (2) large bite block (LBB: 22.5 mm for vowels and 10 mm for CV stimuli) and small bite block (SBB: 2.5 mm for vowels and 5 mm for CV stimuli). The postconversation subtest included two conditions: jaw-free, and 10 mm bite block. Productions were recorded using a digital audio tape recorder and a directional microphone. Recordings were analyzed with both temporal and spectral measures. *Results*: The data suggests that compensation was not occurring “on-line” during vowel production, but that compensatory strategies may develop over time. There appear to be individual differences in the ability to compensate. *Conclusions*: Compensation to increased jaw opening is not as immediate nor as complete as previously thought. Compensatory strategies may develop over time, and consonants appear to require a long period of speech adaptation. *Relevance to current work:* This study examined the adaptation of speech over time using a bite block for static perturbation. The study also used spectral analysis to examine the extent and timeline of consonant adaptation.

McFarland, D. H., Baum, S. R., & Chabot, C. (1996). Speech compensation to structural modifications of the oral cavity. *The Journal of the Acoustical Society of America*, *100*, 1093-1104. https://doi.org/10.1121/1.416286

Objective: The purpose of this study was to examine speech production adaptations and compensations to modifications made to the physical anatomy of the oral cavity. *Method:* Fifteen adult female native French speakers (without a history of communication disorders) participated in the study. Each subject was fitted with two artificial palates, one being 6 mm thick at the midline and the other being 3 mm thick at the midline. The stimuli used in this study included the vowels [i a u] produced in isolation, the voiceless stop consonants [p t k] produced preceding the vowels, and the fricatives [s ʃ] also produced preceding the vowels. Five repetitions of each stimulus were elicited in random order under perturbed and unperturbed conditions. Three conditions were included in the experiment: (1) no artificial palate, (2) thin (3 mm) artificial palate, (3) and thick (6 mm) artificial palate. Data were collected using a digital audio tape recorder and a directional microphone. Vowel and consonant durations, spectral mean, and formant frequencies were determined by segmenting waveforms. Perceptual analysis was also performed by 10 adult native French speakers who were unaware of the purposes of the study, had no history of communication disorders, and passed an audiometric screening. Six perceptual tests comprised of isolated vowel and consonant segments (one for each phoneme and condition) were created. Consonants were played isolated of their vowel context to avoid contaminating effects. Stimuli were presented in a random order via headphones, and raters judged the quality of the stimuli on a five-point scale, with the anchor words "unintelligible" and "perfect." *Results*: The spectral mean of fricatives changed significantly under perturbed conditions, while no significant changes were observed for vowels or stop consonants. *Conclusions:* Artificial palates have much less effect on the acoustic and perceptual parameters of vowels than do bite blocks. The jaw is free to move in the case of the artificial palate, which allows for a rapid change in oral form to produce typical vowels. Fricatives, however, appear to be highly susceptible to the perturbing effects of the artificial palate, as supported by acoustic and perceptual data. Acoustic data showed spectral changes and significantly lower ratings for fricatives under perturbed conditions. It appears that speech compensation for at least a subset of speech sounds appears to improve over time. Patterns of compensation to bite blocks and artificial palates differ due to differences in effect upon the mandible and alveolar ridge. *Relevance to the current work:* The study used both acoustic and perceptual analysis to examine speech adaptation to static perturbation.

McLeod, S., & Crowe, K. (2018). Children's Consonant Acquisition in 27 Languages: A Cross-Linguistic Review. *American Journal of Speech-Language Pathology*, *27*, 1546–1571. https://doi.org/10.1044/2018_ajslp-17-0100

Objective: The aim of this study was to provide a cross-linguistic review of consonant phonemes to provide information to speech-language pathologists regarding children's developmental capacity. *Method*: A cross-linguistic review of 60 articles describing 64 studies of consonant acquisition was undertaken. These 64 studies described consonant acquisition by a total of 26,007 children from 31 countries in 27 languages. *Results*: Most of studies examined were cross-sectional and assessed consonant acquisition through single word production. Overall, most consonants, across languages, were found to be acquired by 5;0 years old. /s/ was one of the phonemes in which the 90% acquisition level (when 90% of children have acquired that phoneme) was between ages 6;0 and 6;11 years old. *Conclusions*: Consonants are acquired at a young age throughout the world and in various languages. Most consonants are typically acquired by age 5;0, though some phonemes, such as /s/ and /ð/, were noted to be acquired after age 5;0. *Relevance to the current work*: This study examined the typical age of acquisition of consonant phonemes, including /s/.

McLeod, S., & Searl, J. (2006). Adaptation to an electropalatograph palate: Acoustic, impressionistic, and perceptual data. *American Journal of Speech-Language Pathology, 15*, 192–206. https://doi.org/10.1044/1058-0360(2006/018)

Objective: The purpose of this study was to evaluate acoustic, perceptual, and speaker-perceived adaptation to an electropalatograph over time. *Method:* Seven adults (3 female and 4 male) with typical speech wore an EPG and pseudo-EPG palate over two days. They participated in a variety of speech tasks (i.e., counting, syllables, "The Rainbow Passage") at sixteen different time points across the two days. Pseudo-EPG palates were worn during the first day, and EPG palates were worn during the second day. Acoustic measures of spectral mean were taken, perceptual analysis was completed by a speech-language pathologist, and participants rated their perception of the impact of wearing the palate. *Results:* An immediate, significant decrease in spectral mean was observed following insertion of the pseudo-EPG palate, and mean values did not increase to a value comparable to baseline until speakers wore the palate for 120 minutes. *Conclusion:* Palatal perturbation may induce changes in tongue configuration and, therefore, oral aerodynamics which could cause the decrease noted in spectral mean for /s/ production. *Relevance to the current work:* This study examined acoustic adaptation to perturbation over time for production of the /s/ phoneme.

Nissen, S. L., & Fox, R. A. (2009). Acoustic and spectral patterns in young children's stop consonant productions. *The Journal of the Acoustical Society of America*, *126*, 1369–1378. https://doi.org/10.1121/1.3192350

Objective: The purpose of this study was to examine the acoustic and spectral patterns of stop articulation in the speech of children. *Methods:* Consonants /p/, /t/, and /k/ were produced by a group of native American English speaking adults and typically-developing children ages 3-5. Target consonants were produced in the following words: *peanut, pocket, Poohbear, teapot, Thomas, toothbrush, key, car*, and *cougar,* which were repeated three times in the carrier phrase *This is a* ____ *again.* Targets were segmented, and their spectral moments measures were computed. *Results:* Acoustic and spectral moments measures (except kurtosis) of stop consonants varied significantly depending on vowel context and place of articulation. Differences in spectral slope, mean, and skewness were significant for adult and 5-year-old speakers. *Conclusion:* Sex-specific differences in prepubescent children's speech patterns may be associated with cultural expectations. *Relevance to the current study:* This study examined the first four spectral moments of consonant phonemes.

Nittrouer, S. (1995). Children learn separate aspects of speech production at different rates: Evidence from spectral moments, *The Journal of the Acoustical Society of America, 97*, 520–530. https://doi.org/10.1121/1.412278

Objective: The purpose of this study was to test the hypotheses that 1) children's articulatory gestures are not as precisely specified as are adults', and that 2) certain gesture patterns achieve adult-like accuracy prior to others. *Methods:* The first, third, and fourth spectral moments were derived for fricatives /s/ and /ʃ/ and stop-bursts noises from /t/ and /k/ in thirty children (3-7 years of age) and ten adults (20-40 years of age). Speech samples were elicited in response to pictures (not imitation) and were recorded in a sound booth, 9 inches from microphone. *Results:* First spectral moments for fricatives showed stronger consonant effects for adults' samples than for children's samples. There was no significant difference between adults' and children's productions of stop-burst noise. It was also found that children's first spectral moments of /k/ varied more than adults' as a result of vowel environments. *Conclusions:* The difference between adults' and children's consonant effects for first spectral moments of fricatives provides evidence that supports the hypothesis that children's articulatory gestures are not as precisely specified as those of adults. The hypothesis that children achieve adult-like accuracy with gesture patterns of some phonemes faster than others is supported by the finding that there was no difference between the spectral moments of stop consonant bursts, indicating that children become more accurate with the gesture patterns of stops faster than they do with the gesture patterns of fricatives. *Relevance to the current work:* This study used spectral moments to quantify the precision of articulatory gestures in multiple phonemes, including /s/.

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. *The Journal of the Acoustical Society of America, 93*, 2948-2961. https://doi.org/10.1121/1.405814

Objective: The purpose of this study was to examine motor equivalence in in the form of reciprocally varying articulatory contributions. *Method*: An electro-magnetic midsagittal articulometer (EMMA) was used to track the movements of the upper lip, lower lip and tongue dorsum of four typical English-speaking males during production of the /u/ vowel in the phrase *Ma, who hid it*. EMMA output voltages were digitized at 312.5 Hz. Signals were then separated into synchronized acoustic and articulatory signal streams and analyzed. *Results:* Three of the four participants demonstrated weak negative correlations between lip rounding and tongue raising, supporting the motor equivalence hypothesis. *Conclusion:* The findings of this study provided preliminary support for motor equivalence at the area-function-to-acoustic level. *Relevance to the current work:* This study used kinematic measures to study motor equivalence through articulatory movements.

Smit, A. B., Hand, L., Freilinger, J. J., Bernthal, J. E., & Bird, A. (1990). The Iowa articulation norms project and its Nebraska replication. *The Journal of Speech and Hearing Disorders, 55*, 779-798.

Objective: The purpose of this study was to obtain data regarding normative speech sound acquisition in the state of Iowa. The study was later replicated for the state of Nebraska. *Method*: The participants of this study were children in the following age groups: 3:0, 3:6, 4:0, 4:6, 5:0, 5:6, 6:0, 7:0, 8:0, 9:0. Children within 2.5 months of target ages from 3:0-5:6 were included, as well as children who were within 3.5 months of the target ages from 6:0-9:0. All child participants had typical hearing and spoke a standard Midwestern dialect. The sample was designed to represent the population of each state on the basis of parent education level, sex, and population density. Whenever possible, children were selected as subjects at random. A single-word assessment was created to evaluate all consonants in word-initial and word-final positions, with the exception of /ʒ/ and /ð/. The assessment utilized photographic stimuli, arranged into semantic categories, to increase the probability of spontaneous naming. A narrow system of transcription was used by examiners, and acceptable responses were outlined in detail to ensure consistency. All examiners were trained in the transcription of data, and interrater reliability was established. A total score was given on the assessment instrument, based on the number of acceptable responses given. Then, the percentage of acceptable responses to each phoneme was calculated for each age group according to sex. *Results*: Nasals, glides, and stops were found to develop early, while fricatives, affricates, and liquids were not mastered until later ages. It is noted that for the /s/ phoneme, only 90% of children reached mastery by age 9 in both word-initial and word-final positions, making /s/ one of the latest-developing phonemes. *Conclusions*: Phonemes are typically developed in roughly the same order. Developing norms for typical acquisition age can inform appropriateness of articulation therapy based on age. It is also important to note that the criteria used to determine whether a phoneme production is acceptable can significantly impact results. *Relevance to the current work:* This study examined the typical age of acquisition of consonant phonemes, including /s/.

Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics*, *17*, 3-45.

Objective: The objective of this article was to examine (1) relations between vocal-tract configurations and the properties of the sound that results from these articulations and (2) relations between acoustic parameters of speech and the auditory responses they provoke. The author provided schematization of how acoustic parameters are affected by articulatory parameters. He proposed that there are certain ranges of the articulatory parameter within which the acoustic parameter is very sensitive to articulatory changes. Within these ranges, acoustic attributes often undergo rapid, qualitative changes as the articulatory parameter changes, resulting in perceptual differences. *Relevance to the current work*: This article describes how slight articulatory movements have the ability to drastically change acoustic and perceptual features of speech.

Subtelny, J. D., Oya, N., & Subtelny, J. (1972). Cineradiographic study of sibilants. *Folia Phoniatrica Et Logopaedica*, *24*, 30–50. https://doi.org/10.1159/000263541

Objective: The aim of this study was to provide insight into the relationship between sibilants and coarticulation. *Method:* Ten adult speakers with normal occlusion participated in the study. Participants produced /s/ and /u/ in isolation and in the sentence, *Sister Suzy saw Sam,* during cephalometric cineradiographic exposure at a speed of 240 fps. Individual frames were traced and measured for analysis at the midpoint of sibilants and their adjacent vowels to determine the effect of vowel positions on sibilant production. *Results:* Positions for the mandible and the tongue tip were extremely consistent during each sibilant production, despite coarticulation. Measures of the interincisal opening and tongue tip (relative to the upper incisors) varied less than 1mm. Consistency was also noted for the length of lingua-dental constrictions, averaging about 1 mm with length approximating 4 mm. Positioning of the tongue body and lip opening were more variable than positioning of the tongue tip and mandible. *Conclusions:* A high degree of precision in mandibular and tongue tip positioning is characteristic of normal sibilant articulation, and this precision is consistent across articulatory contexts. Other articulatory movements, such as tongue body placement and lip opening, are more variable, and are therefore more affected by vowel context. *Relevance to the current work:* This study examined positioning of the tongue and mandible for production of typical sibilants.

Tasko, S. M., & Westbury, J. R. (2002). Defining and measuring speech movement events. *Journal of Speech, Language, and Hearing Research, 45*, 127-42.

Objective: The purpose of this study was to define and measure speech movement events based upon the observation that speech movement waveforms are smooth and continuous. *Method:* Speech materials recorded from 18 young, healthy, native English speaking adults were analyzed. Each speaker read an expanded version of the Hunter script, recorded in four separate recordings; data acquisition was accomplished using the University of Wisconsin X-ray Microbeam system. Articulatory motions were tracked using the midsagittal positions of small gold pellets glued to and around the oral cavity. *Results:* A method of parsing speech movements into *strokes* was proposed, where a stroke is the period between two successive local minima in the speed history of articulator point. Also, this study found that the acoustic timing of alveolar fricatives did not seem to relate to the kinematic features of strokes in any way. *Conclusion:* This approach (i.e., parsing speech into strokes) is most appropriately used for data derived from electromagnetic articulography, infrared video, or other point-tracking techniques. An advantage of this system is that strokes can be defined completely within the body, and therefore can be applied to all types of motor tasks. *Relevance to the current work:* This study examines methods to kinematically parse speech.

Tjaden, K., & Turner, G. S. (1997). Spectral properties of fricatives in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *40*, 1358-72. https://doi.org/10.1044/jslhr.4006.1358

Objective: The purpose of this study was to quantify and compare the spectral characteristics of word initial /s/ and /ʃ/ as produced by individuals with ALS and typically-speaking controls. *Method*: 7 individuals with ALS presenting with mild to moderate speech intelligibility deficits and 7 typically-speaking individuals participated in this study. Each speaker read the Farm Passage at three different rates – habitual, fast, and slow. Acoustic data were recorded using a Shure SM10A, unidirectional, head-mounted microphone, and a magnitude production paradigm was used to elicit speaking rate variation. Nine target words containing initial /s/ were identified and subsequently analyzed acoustically using CSpeech. Four graduate student judges rated consonant precision for the passages read at habitual rate. *Results:* Females with ALS were found to produce /s/ with lower-frequency noise than typically-speaking females, which could be indicative of a more posterior constriction, a wider or longer constriction, and/or reduced flow. It was also found that the speakers with ALS typically produced /ʃ/ with higher frequency noise than typically speaking individuals of the same gender. *Conclusions:* The spectra of /s/ and /ʃ/, as produced by speakers with ALS, are qualitatively different from typical speakers. These acoustic differences indicate articulatory differences in production. *Relevance to the current work:* This study examined the spectral differences between /s/ and /ʃ/ as produced by healthy individuals and individuals with ALS.

Wilcox, K. A., Stephens, M. I., & Daniloff, R. G. (1985). Mandibular position during children's defective /s/ productions. *Journal of Communication Disorders*, *18*, 273–283. https://doi.org/10.1016/0021-9924(85)90004-8

Objective: The purpose of this study was to examine mandibular displacement during /s/ production. *Method*: Eight children in total participated in the study. Two children were normally articulating controls, two were frontal /s/ misarticulators, two were latera /s/ misarticulators, and the final two were tongue retracting /s/ misarticulators. Each child read a list of 34 sentences two times each while their mandibular movements were tracked using a mercury strain gauge. *Results:* Children with a retracted tongue placement had significantly greater jaw displacement for /s/ than any of the other groups, while children with a lateralized /s/ has a significantly more closed jaw position than the other groups did. No significant difference for jaw displacement was noted between control speakers and frontal /s/ misarticulators, although mean values of jaw displacement were higher in frontal /s/ misarticulators. *Conclusion:* Children who misarticulate the /s/ phoneme exhibit different mandibular positions during /s/ productions, each unique to a particular pattern of misarticulation. *Relevance to the current work:* This study examined jaw displacement for /s/ production.

APPENDIX B

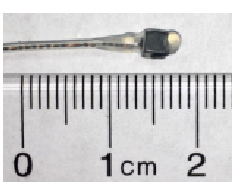
Informed Consent

Consent to be a Research Subject

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

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

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



tracking sensor

bite block

Risks/Discomforts

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

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

Benefits

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

Confidentiality

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

Compensation

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

Participation

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

Questions about the Research

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

Questions about Your Rights as Research Participants

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

Statement of Consent

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

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

APPENDIX C

Stimulus Phrases

Stimuli- repeat 5 times every 2 minutes

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

I'm an owl that hoots

The blue spot is on the black key again

APPENDIX D

Kinematic Descriptive Statistics

Table 5

Mean and Standard Deviation of Tongue Back Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	10.48	2.87
	Male	10.2	4.36
BB2	Female	8.21	3.83
	Male	11.47	2.52
BB4	Female	8.22	4.56
	Male	10.78	2.72
BB6	Female	10.46	3.50
	Male	11.53	4.74
PostBB	Female	9.39	3.87
	Male	9.97	2.21
PreBB	Female	10.74	2.82
	Male	10.65	2.79

Table 6

Mean and Standard Deviation of Tongue Mid Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	11.72	2.52
	Male	11.8	4.20
BB2	Female	10.28	4.06
	Male	11.69	2.46
BB4	Female	9.57	4.01
	Male	11.73	4.90
BB6	Female	10.64	3.41
	Male	12.52	6.22
PostBB	Female	10.16	3.39
	Male	10.97	3.22
PreBB	Female	12.18	3.00
	Male	11.08	3.37

Table 7

Mean and Standard Deviation of Tongue Front Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	13.88	2.50
	Male	13.34	3.75
BB2	Female	12.44	3.55
	Male	11.93	4.28
BB4	Female	11.83	3.05
	Male	12.41	5.02
BB6	Female	11.62	2.63
	Male	12.62	6.01
PostBB	Female	12.30	2.44
	Male	11.43	3.43
PreBB	Female	14.57	3.48
	Male	12.35	4.57

Table 8

Mean and Standard Deviation of Jaw Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	11.44	2.38
	Male	10.10	3.87
BB2	Female	2.51	1.65
	Male	2.87	1.01
BB4	Female	2.06	1.22
	Male	2.18	0.75
BB6	Female	3.51	1.84
	Male	2.87	1.50
PostBB	Female	3.05	1.85
	Male	2.32	0.76
PreBB	Female	12.36	3.70
	Male	10.10	3.87

Table 9

Mean and Standard Deviation of Lower Lip Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	5.60	2.84
	Male	3.78	1.67
BB2	Female	5.32	2.67
	Male	5.37	3.07
BB4	Female	8.09	3.98
	Male	5.05	1.67
BB6	Female	6.52	1.88
	Male	4.13	1.37
PostBB	Female	9.03	2.53
	Male	9.97	3.70
PreBB	Female	11.94	2.31
	Male	8.88	1.87

Table 10

Mean and Standard Deviation of Upper Lip Displacement (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	2.83	1.85
	Male	2.76	1.12
BB2	Female	2.42	1.72
	Male	3.25	1.33
BB4	Female	3.35	1.43
	Male	3.69	1.71
BB6	Female	3.13	1.92
	Male	2.83	0.86
PostBB	Female	3.42	2.07
	Male	5.32	2.36
PreBB	Female	3.35	1.42
	Male	3.32	0.68

Table 11

Mean and Standard Deviation of Tongue Back Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	115.23	28.71
	Male	133.84	30.72
BB2	Female	104.70	34.73
	Male	142.30	28.29
BB4	Female	138.80	42.32
	Male	157.53	40.47
BB6	Female	115.17	38.39
	Male	148.12	31.65
PostBB	Female	145.15	29.65
	Male	193.02	81.01
PreBB	Female	134.30	31.87
	Male	169.85	46.60

Table 12

Mean and Standard Deviation of Tongue Mid Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	117.41	45.25
	Male	132.32	22.60
BB2	Female	113.23	45.84
	Male	146.11	47.66
BB4	Female	136.95	45.87
	Male	150.24	36.88
BB6	Female	124.74	33.45
	Male	133.30	33.52
PostBB	Female	141.75	38.65
	Male	182.54	61.24
PreBB	Female	139.42	31.63
	Male	159.37	54.17

Table 13

Mean and Standard Deviation of Tongue Front Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	153.91	55.62
	Male	137.13	40.39
BB2	Female	136.89	57.27
	Male	154.42	47.90
BB4	Female	152.02	52.70
	Male	160.50	43.10
BB6	Female	155.54	51.80
	Male	143.51	49.26
PostBB	Female	149.59	51.24
	Male	184.76	51.08
PreBB	Female	137.87	40.09
	Male	183.33	64.83

Table 14

Mean and Standard Deviation of Jaw Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	38.07	23.37
	Male	24.99	9.54
BB2	Female	38.53	18.78
	Male	28.84	10.13
BB4	Female	46.95	20.18
	Male	29.78	7.92
BB6	Female	49.62	10.76
	Male	33.45	12.23
PostBB	Female	132.77	84.77
	Male	128.85	38.48
PreBB	Female	112.51	22.53
	Male	131.21	45.71

Table 15

Mean and Standard Deviation of Lower Lip Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	85.11	50.11
	Male	75.95	53.84
BB2	Female	117.73	77.68
	Male	101.89	79.74
BB4	Female	157.44	127.81
	Male	89.99	54.45
BB6	Female	123.54	80.42
	Male	87.74	46.91
PostBB	Female	133.52	41.76
	Male	157.14	75.60
PreBB	Female	131.43	25.67
	Male	125.71	29.85

Table 16

Mean and Standard Deviation of Upper Lip Maximum Velocity (mm/s) Across Recordings

	Gender	Mean	SD
BB0	Female	38.86	21.15
	Male	60.20	42.05
BB2	Female	37.56	14.74
	Male	60.85	49.08
BB4	Female	48.33	15.25
	Male	52.01	22.32
BB6	Female	47.14	10.68
	Male	57.43	36.84
PostBB	Female	44.78	15.64
	Male	82.79	81.14
PreBB	Female	42.23	8.85
	Male	51.73	20.61

Table 17

Mean and Standard Deviation of Jaw Contribution to the Movements of the Tongue Back (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	2.08	1.22
	Male	1.39	0.85
BB2	Female	1.80	0.99
	Male	1.79	0.63
BB4	Female	3.01	1.55
	Male	2.35	1.30
BB6	Female	2.64	1.48
	Male	1.92	0.68
PostBB	Female	9.49	3.40
	Male	6.90	2.60
PreBB	Female	8.45	1.62
	Male	6.01	1.73

Table 18

Mean and Standard Deviation of Jaw Contribution to the Movements of the Tongue Mid (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	2.21	1.31
	Male	1.46	0.88
BB2	Female	1.88	1.06
	Male	1.89	0.63
BB4	Female	3.17	1.62
	Male	2.48	1.31
BB6	Female	2.75	1.51
	Male	2.03	0.70
PostBB	Female	10.34	3.38
	Male	7.69	2.66
PreBB	Female	9.33	1.70
	Male	6.81	2.00

Table 19

Mean and Standard Deviation of Jaw Contribution to the Movements of the Tongue Front (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	2.28	1.42
	Male	1.53	0.92
BB2	Female	1.93	1.09
	Male	1.99	0.66
BB4	Female	3.25	1.67
	Male	2.61	1.34
BB6	Female	2.84	1.66
	Male	2.12	0.71
PostBB	Female	10.92	3.43
	Male	8.53	2.97
PreBB	Female	9.96	1.95
	Male	7.58	2.18

Table 20

Mean and Standard Deviation of Jaw Contribution to the Movements of the Lower Lip (mm) Across Recordings

	Gender	Mean	SD
BB0	Female	2.66	1.81
	Male	1.77	1.08
BB2	Female	2.16	1.29
	Male	2.30	0.76
BB4	Female	3.67	1.92
	Male	3.02	1.51
BB6	Female	3.18	1.99
	Male	2.45	0.81
PostBB	Female	13.33	3.59
	Male	11.15	4.29
PreBB	Female	12.45	2.52
	Male	9.95	3.07

APPENDIX E

Acoustic Descriptive Statistics

Table 21

Mean and Standard Deviation of Spectral Mean (Hz) Across Recordings

	Gender	Mean	SD
BB0	Female	3450.35	1843.58
	Male	2877.52	1045.20
BB2	Female	3768.81	1658.35
	Male	3339.08	1000.60
BB4	Female	4223.24	1733.13
	Male	3416.14	1050.22
BB6	Female	4113.28	2096.87
	Male	3324.96	931.72
PostBB	Female	4845.68	1667.93
	Male	5282.50	667.89
PreBB	Female	5252.04	797.33
	Male	5559.17	646.69

Table 22

Mean and Standard Deviation of Spectral Standard Deviation Across Recordings

	Gender	Mean	SD
BB0	Female	2493.22	636.07
	Male	2355.01	426.03
BB2	Female	2583.93	434.95
	Male	2349.59	270.68
BB4	Female	2780.68	398.10
	Male	2406.93	184.86
BB6	Female	2580.68	553.67
	Male	2360.07	240.89
PostBB	Female	2293.14	762.60
	Male	2004.45	417.26
PreBB	Female	2621.69	519.01
	Male	1871.42	437.67

Table 23

Mean and Standard Deviation of Spectral Skewness Across Recordings

	Gender	Mean	SD
BB0	Female	2493.22	636.07
	Male	2355.01	426.03
BB2	Female	2583.93	434.95
	Male	2349.59	270.68
BB4	Female	2780.68	398.10
	Male	2406.93	184.86
BB6	Female	2580.68	553.67
	Male	2360.07	240.89
PostBB	Female	2293.14	762.60
	Male	2004.45	417.26
PreBB	Female	2621.69	519.01
	Male	1871.42	437.67

Table 24

Mean and Standard Deviation of Spectral Kurtosis Across Recordings

	Gender	Mean	SD
BB0	Female	2.55	5.64
	Male	0.75	1.59
BB2	Female	1.56	1.97
	Male	0.42	1.54
BB4	Female	0.29	1.78
	Male	0.22	0.93
BB6	Female	1.33	2.13
	Male	0.05	0.81
PostBB	Female	2.53	3.47
	Male	1.37	1.41
PreBB	Female	2.43	5.00
	Male	2.44	2.00