THE EFFECT OF A PSEUDOPALATE ON VOICELESS OBSTRUENT PRODUCTION: A SPECTRAL EVALUATION OF ADAPTATION

by

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Communication Disorders
Brigham Young University
August 2008

BRIGHAM YOUNG UNIVERSITY

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ABSTRACT

THE EFFECT OF A PSEUDOPALATE ON VOICELESS OBSTRUENT PRODUCTION: A SPECTRAL EVALUATION OF ADAPTATION

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Many studies in speech communication have provided valuable findings concerning the kinematic nature of speech articulation. This type of research often involves introducing an oral device to the vocal tract such as lingual pellets, magnets, and different forms of pseudopalates to track the movement and placement of the articulators. This study examined the effect of an electropalatography (EPG) pseudopalate on the production of five voiceless obstruents (/p, t, k, s/ and /ʃ/). Acoustic recordings from 20 adult speakers with typical speech production were made during three different speaking conditions: prior to pseudopalate placement, immediately after placement, and following 20 minutes of conversation. The obstruent articulations were examined in terms of four spectral moments (spectral mean, spectral variance, spectral skewness, and spectral kurtosis). The spectral analysis indicated that placement of a pseudopalate resulted in a statistically significant disturbance of the speaker's obstruent productions. After 20 minutes of conversation with the pseudopalate in place, results of the spectral analysis indicated that participants' productions trended back toward a typical pattern of articulation; however their adaptation was not complete and it remains unclear if further practice with the pseudopalate would result in typical speech production.

ACKNOWLEDGMENTS

Numerous individuals have provided their support, encouragement, and assistance in helping me complete my thesis and masters degree. I want to thank my committee chair and advisors for their support, and for the time and energy they put into polishing my thesis. My husband for his love and support and for the endless hours he spent on formatting, editing, and caring for our daughter while I worked on this project. My parents, without their support and encouragement I never could have completed my education. Lastly, I want to express my gratitude to close family and friends who inspired and motivated me as I worked on this great endeavor. I will be eternally grateful for the influence of all these individuals throughout my life, without them I never would have been able to accomplish my dreams.

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Introduction

Methods of Measuring the Kinematic Nature of Speech Production

Speech production is a dynamic process essential for communicating and interacting with others. The articulatory elements involved in speech production are difficult to visualize due to the enclosed nature of the tongue, palate, and teeth within the vocal tract. A variety of methods have been designed to track the movement and placement of the articulators, such as x-ray microbeam (Fujimura, Kiritani, & Ishida, 1972), magnet tracking (Dromey, Nissen, Nohr, & Fletcher, 2005; Nissen, Dromey, & Wheeler, 2008), ultrasound (Kent, 1997; Stone, 1990; Stone, Faber, Raphael, & Shawker, 1992), and electropalatography (Fletcher, McCutcheon, & Wolf, 1975; Hardcastle, Gibbon, & Jones, 1991).

X-ray microbeam technology uses a narrow high-energy x-ray beam to track gold pellets which are attached to articulators while simultaneously acquiring physiological data (Westbury, 1994). These gold pellets are 2-3 mm in diameter and are attached at desired points using Ketac (a dental adhesive). Pellets are also attached to threads for pellet retrieval in case of aspiration. Subsequently, the pellet movements are tracked using the x-ray microbeam during speech production.

The JT-3 jaw tracking magnet system consists of a lightweight headset and 24 sensors positioned around each side of a subject’s face (Dromey et al., 2005). The sensors are designed to track lateral, vertical, and anterior-posterior movements of a single magnet attached to the tongue (Dromey et al., 2005; Nissen et al., 2008). Data obtained by this device allow researchers to study 3-dimensional tongue movement during speech.

Ultrasound technology emits ultra-high frequency sound waves which pass through the body and encounter various tissues and spaces (Stone, 1990). At these boundaries part of the sound beam is reflected, creating waves which can be used to examine internal organs such as the tongue and vocal folds during speech production (Kent, 1997). Unlike x-ray microbeam technology, ultrasound avoids the possible side-effects of radiation; however, the technology is somewhat expensive and not widely available to researchers or clinicians.

EPG or dynamic palatometry is employed in tracking articulatory tongue-palate contacts. EPG consists of a custom fit soft pseudopalate containing 60 to 118 electrodes or sensors (Fletcher et al., 1975). The pseudopalate closely fits the contours of the teeth and palate, extending posteriorly to the back molars. The timing and location of tongue-palate contacts during continuous speech are transmitted and recorded through a series of wires which exit the mouth and convey the data to a computer display screen (Hardcastle, Gibbon, & Jones, 1991).

EPG is a powerful tool which provides clinicians and clients with dynamic real-time visual feedback. Connection to a computer screen allows clinicians and clients to observe tongue-palatal contacts during speech. Electrodes are activated each time the tongue contacts the palate. An image on the graphic display screen identifies or lights up which sensors have been activated or contacted on the pseudopalate. This unique system allows clients to observe normally unseen tongue-palate contacts during speech (Fletcher, Dagenais, & Critz-Crosby, 1991).

Clinically, EPG may be an effective alternative method of speech remediation for individuals that have not benefited from traditional therapy techniques. It provides clinicians the opportunity to gather specific data regarding a client’s articulation performance and allows the client to observe and possibly understand the errors in their articulation. A split screen display is often used to depict the target articulatory pattern alongside the client’s articulatory patterns. The client is then instructed about the manner in which to achieve specific speech production targets (i.e., syllables, words, and phrases). Visual feedback provided by the EPG system also helps a client to self-monitor their productions and recognize their successes and progress, as well as develop accurate articulatory movements.

A potential drawback to EPG and other articulatory tracking technologies is that many of these methods require introducing an oral device or physical structure within the vocal tract such as lingual pellets, magnets, or different forms of pseudopalates, which may interfere with an individual's usual patterns of articulation. In addition, these types of devices might also inhibit the sensory feedback necessary for typical speech production.

Sensorimotor Feedback and Articulatory Adaptation

Introducing a foreign object into the vocal tract can negatively affect speech articulation; however, individuals are often able to adapt their articulation to compensate for physical differences or perturbations in the speech mechanism. According to McFarland, Baum, and Chabot (1996) an individual's capacity to adapt to perturbations can be attributed to sensory feedback and their ability to formulate new articulatory motor programs in response to environmental changes. Sensory feedback includes auditory and somatosensory (temperature, pain, pressure, movement, and posture) information, both of which inform the brain about the accuracy of the body's motor output in comparison to the intended output. It is postulated that this feedback loop allows individuals to track the execution of their movements and to fine-tune them according to the feedback they receive.

A recent study by Houde and Jordan (2002) examined sensorimotor adaptation and its role in adapting speech production. Eight native English speaking participants produced a series of vowels (/i, ɪ, ɛ, æ, ɑ/) while listening to digitally altered auditory feedback of their speech. To minimize bone conduction effects, subjects were instructed to whisper rather than vocalize the stimuli. The modified feedback caused the participants to hear /ɑ/ or /i/ when they produced /ɛ/. The results of this adaptation experiment revealed that participants adjusted their productions to compensate for the altered feedback by shifting their formants for /ɛ/ from the original values. Furthermore, these compensations were retained when the speakers were subjected to masking noise during the testing procedures. The findings of this study support the theory that speech exhibits sensorimotor adaptation and suggest that auditory feedback plays an important role in guiding an individual’s ability to produce compensatory articulatory productions.

Motor Equivalence

Adaptation of the speech mechanism is in part made possible by the ability of the articulatory system to produce the same acoustic percept or configuration in a variety of ways (McFarland & Baum, 1995). This idea is representative of the theory of *speech equifinality*, more commonly known as *motor equivalence*. Motor equivalence suggests that the same articulatory goal can be achieved through various kinematic executions utilizing different muscle groups to meet the environmental demands (Kelso & Tuller, 1983). According to this principle, speakers are capable of producing phonemes such as /s/ or /t/, with slightly different tongue and palate placements and movements, while still achieving a similar perceptual result. The use of both sensory feedback and motor equivalence are considered important elements in enabling the phenomenon of articulatory adaptation to perturbations encountered during speech production.

Articulatory Adaptation to Structural Perturbation of the Vocal Tract

McFarland et al. (1996) describe perturbations of speech production as belonging to two categories: functional and structural. Functional perturbations are defined as modifications which interfere with the movements or positioning of the articulators. Structural modifications do not directly hinder movement, but introduce physical changes to the vocal tract. According to the definition put forth by McFarland et al., structural perturbations might include dental prostheses and orthodontic devices, bite blocks, pellet markers, lingual magnets, or an artificial pseudopalate.

Dental prostheses. Reports of speech alterations due to dental prostheses can be found in the literature (Garber, Speidel, & Glass, 1977; Hamlet, Cullison, & Stone 1979). Hamlet and Stone (1982) assessed the speech adaptation of participants with a history of articulation disorders to dental prostheses. All 13 subjects had overcome their articulation problems in childhood and had typical sounding speech. Each subject was fitted with two experimental dental prostheses that were 1 mm and 4 mm thick. These prostheses were designed to track the tongue contact patterns of the subjects' utterances during recordings, and to present a structural modification. The 1 mm prosthesis was only intended for the purpose of initially assessing natural speech productions. Recordings were then taken at two different intervals, at the onset of the study, and following two weeks of speaking with the 4 mm thick prosthesis in place. The focus of the data analysis was on the fricative productions of /s/ and /z/. The speech productions were elicited by having the participants read short phrases with the target segments, such as *a ceiling light* or *a xylophone*. Of the 13 participants involved in the study, 7 were found to have achieved successful speech adaptation, as determined by the speakers' subjective impressions and an examination of their tongue contact patterns. These patterns showed compensatory lingual groove narrowing during the baseline measures and a return to typical groove width following two weeks of speech experience with the prosthesis in place. The results of this study suggest that speech is typically affected by oral devices, but that partial or complete adaptation is possible.

Bite block studies. Gay, Lindblom, and Lubker (1981) studied the compensatory articulations and adaptation strategies demonstrated by subjects in bite-block versus normal conditions through the use of formant frequency measurements and lateral view x-rays. Five adult male participants produced the American English vowels /i, ɑ, u/ and /o/ with and without a bite block in place. Following the collection of data using x-rays and acoustic recordings, Gay et al. (1981) used informal listening tasks and spectrographic measurements in determining that speakers were able to successfully compensate for the bite blocks. The researchers found that the shapes of the oral cavity used to produce the vowels and the resulting formant patterns indicated that the speakers were able to compensate for the presence of the bite-blocks by using lip and tongue *super-shapes* or extreme elaborations of typical articulation. This study provides evidence that some speakers are able to utilize compensatory behaviors or articulatory adaptations when environmental perturbations are present.

Pellet markers. In a study conducted in 1999, Weismer and Bunton examined the influence of small pellet markers used in x-ray microbeam analysis on typical speech production behavior. Twenty-one adult speakers of American English were asked to produce the phrase, *she had your dark suit in greasy wash water all year*, three times prior to pellet placement and five times with a series of pellets in place. A total of 11 pellets were placed on each subject, 4 on the tongue, 2 on the mandible, 2 on the lips, 2 on the nose, and 1 on the buccal surface of the maxillary incisors. Once the pellets were in place, the participants' lingual placement and movement was tracked using x-ray microbeam technology during production of the elicitation phrase. The results of Weismer and Bunton's study indicated subtle trends in which speakers' productions reflected articulatory adjustments to avoid contact between the pellets and the upper, anterior regions of the vocal tract. Specifically, they discovered that female subjects opted to articulate with a more open mouth with the lingual pellets in place and all subjects except for one retracted the anterior pellets away from the alveolar ridge while speaking. These findings provide some support for the notion that speakers will often adapt their articulation patterns to compensate for structural perturbations in the oral cavity.

Lingual magnets. A thesis by Weaver in 2005 also examined the effects that a small tracking device, attached to various regions of the tongue, had on the production of running speech and the subjects' rate of adaptation to the structural perturbation. Specifically, the author studied the effect that a small magnet (1.2 mm thick and 7 mm in diameter) attached to the tongue had on the spectral characteristics of a participant's production of the fricatives /s/ and /ʃ/. Participants in the study included ten college-aged, native speakers of American English. The stimulus phrase, *Allison had to miss a sunny vacation at Shellfish Bay*, was repeated five times under four speaking conditions: prior to magnet placement, immediately following placement, following 5 minutes of conversation, and following 10 minutes of conversation. Two separate recording sessions were conducted to evaluate the possible effect of two different magnet placements (10 and 15 mm from the tongue tip). The elicited recordings were subsequently analyzed using acoustic and spectral moment analyses. These analyses revealed that the initial placement of the magnet had a statistically significant effect on the spectral mean and variance of the /ʃ/ productions. However, following 5 minutes of conversation, participants had been able to adapt their fricative productions back within typical articulatory patterns, with no significant differences being observed in any spectral measures for /s/ or /ʃ/. These results support the theory that individuals are capable of adapting to articulatory perturbations following a practice period.

Artificial pseudopalates. Research conducted by McFarland et al. (1996) has also investigated the effects of thin and thick palatal devices on articulation at the syllable level in contrast to typical speaking conditions. Stimuli examined in the study included CV syllables created by combining the obstruent consonants /p, t, k, s/ and /ʃ/ with the vowels /i, ɑ/ and /u/. Acoustic and perceptual data collected from three different speaking conditions (without palate, immediately following palate placement, and following 15 minutes of adaptation) revealed minimal to no significant differences in the articulatory parameters of the vowels in any condition. However, significant perturbing effects were noted for /s/ on all spectral and perceptual aspects under the with-palate conditions. The researchers also found that after 15 minutes of time with the pseudopalate in place, the participants' speech articulation adapted back toward their typical patterns of production, thereby further supporting the theory of articulatory adaptation.

The role of sensory feedback in an individual's ability to adapt to an artificial palate was specifically examined in a research study performed by Baum and McFarland (1997). The researchers used acoustic and perceptual analyses to determine whether a one hour intensive practice period was sufficient for an individual to adapt their articulation of /s/ to acceptable patterns of production. Participants were instructed to produce the target stimulus /sɑ/ 30 times at five different intervals 15 minutes apart (0, 15, 30, 45, & 60 minutes) with the pseudopalate in place. Subjects were also instructed to produce 30 repetitions of /sɑ/ without the palate in place at time intervals 0 and 60 minutes. The palate was in place for each 15 minute interval between data collection points, during which subjects were instructed to read passages containing numerous /s/ productions to provide increased sensory feedback. This was done in an effort to encourage participant adaptation to the perturbation. Following these procedures, Fourier analysis and perceptual analyses were utilized to assess the presence of an adaptation effect. Their findings indicated that, although compensation was not total, significant acoustic and perceptual improvements were discovered following intensive practice of multiple /s/ productions. These results suggest the development of relatively quick compensatory strategies with the use of intensive target practice, and a sufficient time allotment.

Articulatory Perturbation and Adaptation in Obstruent Sounds

Due to the nature of their articulation and the relatively closed state of the vocal tract during production, obstruent sounds are more sensitive to structural perturbations within the oral cavity than sonorant or vowel-like speech sounds. Obstruent speech segments are generated when a pressurized flow of air meets a complete obstruction or narrow constriction at some point within the vocal tract. The resulting speech sounds are stops and fricatives which are produced with transient noise excitation or a significant degree of frication (Nissen, 2003). Stops and fricatives are therefore two divisions of obstruents.

Stop consonant production. According to Kent (1997), stops are formed by complete occlusion of the vocal tract at some point between the lips and vocal folds. This occlusion occurs when the tongue or lips create a constriction within the vocal tract, resulting in complete obstruction of the outward flow of air through the oral cavity. This phase is usually referred to as the silent gap during which the occlusion is formed and oral pressure increases. Following the silent gap, the stop burst is released which results in aperiodic sound that lasts between 10 to 30 ms (Ferrand, 2007).

Spectrograms of stops depict the aperiodic sound of the stop burst with a vertical line extending into the high frequencies. Due to the transient nature of stops, this line is fairly short in duration. Regarding specific bands of energy, the spectrographic display of bilabial /p/ reflects low frequency acoustic energy between 500 to 1500 Hz. In comparison, lingua-alveolar /t/ is characterized by higher acoustic energy at 2500 to 4000 Hz. This high level of sound energy is created by the small cavity in front of the stop constriction which actively filters the low frequencies and emphasizes the higher frequencies (Ferrand, 2007). Lastly, lingua-velar /k/ is characterized by sound energy at 1500 to 4000 Hz. This range of frequencies is the result of the large oral cavity anterior to the point of constriction.

Fricative consonant production. Fricatives are continuous sounds which have wide bands of energy that are distributed across a broad range of frequencies (Ferrand, 2007). Fricatives, such as /s/ and /ʃ/, are produced when air passes through a narrow supraglottal constriction formed by two articulators in the vocal tract. English fricatives (/ɵ, ð, s, z, ʃ/ and /ʒ/) are typically produced in part by approximating the tongue with the superior portions of the oral cavity such as the upper teeth, alveolar ridge, or the palate. However fricatives can also be produced with other articulatory combinations, as is the case with the labio-dental /f/ and /v/, which are produced by approximating the upper incisors with the lower lip. As this pressurized air flows through the vocal tract it generates turbulence in the region downstream from the constriction (Narayanan & Alwan, 2000; Nissen, 2003; Shriberg & Kent, 1995). This turbulent airflow creates random variations in air pressure which results in the characteristic noise source of fricative sounds.

Spectrograms of fricative productions depict aperiodic sound with energy spread fairly evenly throughout the spectrum. However, the frequency ranges that are reinforced are determined by the position of the articulators and where the sound is produced, thereby creating resonating cavities of differing lengths and shapes. The voiceless fricative /s/ is considered a lingua-alveolar which is produced more anteriorly with a shorter resonating cavity. While /ʃ/ is considered a lingua-palatal which is produced with a longer front resonating cavity and associated lip rounding that tends to extend the front cavity. Acoustically, /s/ fricatives are characterized by sound energy concentrated around 3500 Hz and above, and /ʃ/ is typically characterized by lower sound energy at 2000 Hz and above (Ferrand, 2007). These spectral values will also vary according to inter-speaker characteristics, such as speaker sex, age, and speaking style, as well as differences in individual vocal tract characteristics.

Spectral Moments Analysis

Spectral moments analysis is a technique that has been utilized to examine the spectral characteristics of obstruent speech segments. This technique uses Fast Fourier Transform (FFT) spectra from a single window of analysis (Nissen, 2003). Subsequently, these FFT spectra are then treated as a random probability distribution from which statistical moments (mean, variance, skewness, and kurtosis) can be used to quantitatively describe the spectral energy present in stop burst and fricative segments of sound (Forrest, Weismer, Milenkovic, & Dougall, 1988; Nissen, 2003). These statistical moments (i.e., mean, variance, skewness, and kurtosis) are then used to examine the spectral characteristics of discrete time segments from the target areas of the speech signal.

The first spectral moment examines the centroid, or average energy distribution of a FFT power spectrum. The FFT process describes temporal waveforms, like speech, as frequency components of varying amplitudes. The second moment describes the variability over which the power spectrum is spread (Nissen, 2003). The skewness or spectral tilt of the spectrum distribution is then examined by the third spectral moment. Positive skewness indicates that the median component of the FFT has a higher frequency than the mean. The fourth spectral moment describes the kurtosis or *peakedness* of the energy distribution. A high kurtosis value indicates clearly defined peaks, while a low value indicates a flat distribution (Jongman, Wayland, & Wong, 2000).

Historically, researchers have used this method of analysis to gain insight into the articulation of certain speech sounds without interfering with the processes and mechanisms involved with speech production. Studies have utilized spectral moments analysis to examine the acoustic classification of speech (Forrest et al., 1988, 1990; Jongman et al., 2000; Nissen, 2003), and speech development in children (Fox & Nissen, 2005; Nissen & Fox, 2005; Nittrouer, 1992, 1995). In addition, this method of spectral analysis has also been used to measure the perturbation and adaptation to research techniques that track the kinematics of speech, especially for the production of obstruent sounds that are more easily impacted by the introduction of physical devices into the oral cavity (McFarland et al., 1996; Weaver, 2005; Weismer & Bunton, 1999).

Purpose of Study

Previous studies support the theory that the speech production system is capable of adapting to some degree of articulatory perturbation. Sensory feedback and motor equivalence appear to be the underlying influences which allow for its significant flexibility and compensatory strategies. While numerous adaptation studies have been performed throughout the years, further studies are still required to determine the extent to which an individual can adapt to specific devices, the amount of time required for sufficient adaptation, and the overall effects of various devices on the acoustics of certain phonemes. Thus, the present study investigated a group of typical speakers' ability to adapt their speech production to the placement of a relatively thin pseudopalate in the oral cavity. Specifically, this study addressed the following research questions:

1. Does the placement of a relatively thin artificial pseudopalate result in a significant disturbance in the spectral realization of the voiceless obstruents /p, t, k, s/ and /ʃ/? If so, in what manner are the spectral characteristics of the sounds altered?
2. Do speakers exhibit an adaptation to the artificial pseudopalate after speaking with the device for a short period of time (20 minutes)?

Method

Participants

The acoustic data analyzed in this study were collected in a previous palatometric study conducted by Sanders (2007). Speech recordings from 20 adult participants (10 male and 10 female) with a mean age of 25.2 years of age were acoustically analyzed. Participants were recruited by announcements and fliers. No history of speech abnormalities, jaw problems, hearing impairment, or serious dental abnormalities was reported from any of the participants. All participants underwent a hearing screening to ensure adequate hearing abilities. Each passed the hearing screening bilaterally at 500, 1000, 2000, and 4000 Hz at 15 dB HL. Subsequently, each participant was fitted with pseudopalates based on stone models from their dental impressions.

Procedures and Stimuli

Prior to participation in the aforementioned palatometric study, each participant read and signed an Informed Consent Document approved by the Brigham Young University Institutional Review Board for Human Subjects Research (Appendix). Audio recordings from the previous study were made in an Acoustic Industries 7’ x 7’ single-walled sound booth using an AKG C2000B microphone and a Samson mixpad4 pre-amplifier. The microphone was placed approximately 6 - 7 inches from the mouth for each recording. Speech tokens were recorded at a sampling rate of 48 kHz and a quantization of 16-bits onto a digital analog tape (DAT) recorder (Panasonic SV3800). Prior to testing, each participant was instructed to brush his or her teeth and use mouthwash to cleanse the mouth of any residue that might be present.

The target stimuli (/p, t, k, s, ʃ/) were elicited from the following elicitation sentences: *The boot on top is packed to keep. The boy gave a shout at the sight of the cake.* Each of the sentences were produced by the speakers five times during three different speaking conditions: (a) prior to placement of the pseudopalate in the mouth, (b) immediately after placement of the pseudopalate, and (c) following 20 minutes of conversation with the pseudopalate in place. The target sounds were all in word-initial position and extracted from the words *sight*, *shout*, *top*, *packed*, and *cake*. Thus, the corpus of target sounds included 75 speech tokens from each subject (5 sounds x 5 repetitions x 3 speaking conditions).

Segmentation

Using Adobe Audition version 1.3 (Adobe Systems Incorporated, 2003), segmentation of obstruent targets was conducted using waveform display assisted by spectrographic inspection. A rapid increase in zero crossings and/or spectrographic identification of high frequency energy characterized fricative onset, whereas the intensity minimum prior to vowel periodicity and/or absence of high frequency energy was the offset (Jongman et al., 2000). The onset of the stop burst was characterized by a sharp increase in diffuse noise energy and the rapid increase in zero crossings, with the burst offset defined by a sharp decrease in diffuse noise energy. In addition, the segmented tokens were monitored auditorily to increase the segmentation accuracy.

Segmentation values were then recorded into a text file in milliseconds using a MATLAB program that displayed the segmentation marks superimposed over a display of the token’s waveform. Additionally, 300 randomly selected tokens were independently analyzed by a second individual to test for segmentation accuracy and reliability. The voiceless obstruent boundary measurements were subsequently correlated ($r = .99$, $p < .001$) with the original segmentation values extracted for these same tokens, differing by an average of approximately 1 ms.

Spectral Moments Analysis

The spectral moments analysis was completed following the procedures outlined in previous research which examined the acoustic properties of voiceless obstruents (i.e., Forrest et al., 1988; Fox & Nissen, 2005; Jongman et al., 2000; Nissen & Fox, 2005; Nittrouer, 1995). Using custom software programmed in MATLAB, the measures of spectral mean, spectral variance, spectral skewness, and spectral kurtosis were calculated for each obstruent target segment.

For the stop productions, a normalized power spectra was derived from a 20 ms Hamming window centered +10 ms from the release of the stop burst, which was then pre-emphasized by first-differencing. Although the need for pre-emphasis is reduced when analyzing the spectral characteristics of voiceless sounds, such a procedure is necessary to more effectively compare subsequent results to previously published findings (e.g., Forrest et al., 1988; Fox & Nissen, 2005; Jongman et al., 2000; Nissen & Fox, 2005; Nittrouer, 1995). Using a 1024-point FFT with zero-padding, the spectral amplitudes of a series of frequency points were derived from the complex acoustic signal within the 20 ms window. The fricative segments were spectrally analyzed using a pre-emphasized 40 ms Hamming window located at the middle of the segmented portion of frication. The fricative productions were spectrally analyzed with 2048-point FFTs. For both the stop and fricative analysis, the individual FFT spectra from each segment were converted to normalized power spectra by the following computation:

$$P(k_j) = [P(k_j)/\sum(P(k_1) +\ldots+(k_{512\text{ or }1024})] \tag{1}$$

P = relative power
k = real-valued frequency point (j from 1 to 512 or 1024)

The first frequency point (k_0) or dc component of each recorded sample does not provide useful information and is therefore not utilized when computing the normalized power spectra. The normalized power spectra mentioned above were then considered random distribution probabilities, from which the first four statistical moments were then computed. The spectral mean statistic was computed by taking the sum of each frequency point multiplied by the relative power of that point. Thus, the computation of the spectral mean statistic is as follows:

$$\text{Spectral mean} = \sum [k_j (P_j)] \tag{2}$$

P = relative power
k = real-valued frequency point
j = from 1 to 256 for 512-point FFT spectra
from 1 to 512 for 1024-point FFT spectra

The spectral variance statistic was calculated by taking the sum of each frequency point's squared deviation from the mean. This calculation is summarized in the following notation:

$$\text{Spectral variance} = \sum [(k_j - m_1)^2 P_j] \tag{3}$$

m_1 = spectral mean
P = relative power
k = real-valued frequency point
j = from 1 to 256 for 512-point FFT spectra
from 1 to 512 for 1024-point FFT spectra

The spectral skewness statistic is a reflection of how the acoustic energy is distributed around the mean, also referred to as the spectral tilt. The spectral skewness was computed as follows:

$$\text{Spectral skewness} = \sum [(k_j - m_1)^3 P_j] \tag{4}$$

m_1 = spectral mean
P = relative power
k = real-valued frequency point
j = from 1 to 256 for 512-point FFT spectra
from 1 to 512 for 1024-point FFT spectra

Since a direct comparison of skewness across different levels of variance is inappropriate (Forrest et al., 1988; Nissen, 2003; Nissen & Fox, 2005), the spectral skewness statistic was normalized and expressed as a coefficient. This computation can be expressed as the following:

$$\text{Spectral skewness}_{\text{normalized}} = [m_3/(m_2{}^{3/2})] \tag{5}$$

m_2 = spectral variance
m_3 = spectral skewness

The spectral kurtosis indicates the peakedness of the distribution of spectral energy. A negative kurtic coefficient indicates a relatively flat spectral distribution, whereas a positive coefficient is characteristic of more prominent spectral peaks. The spectral kurtosis was computed as follows:

$$\text{Spectral kurtosis} = \sum [(k_j - m_1)^4 P_j] \tag{6}$$

m_1 = spectral mean
P = relative power
k = real-valued frequency point
j = from 1 to 256 for 512-point FFT spectra
from 1 to 512 for 1024-point FFT spectra

To allow for direct comparisons, the fourth spectral moment was also normalized for differences in spectral variance according to the following calculation:

$$\text{Spectral kurtosis}_{\text{normalized}} = [m_4/(m_2{}^{2}) - 3] \tag{7}$$

m_2 = spectral variance
m_4 = spectral kurtosis

All digital signal processing and acoustic analysis was conducted by custom designed computer programs written in MATLAB. A corpus of test tokens comprised of known acoustic components was utilized to evaluate the accuracy and reliability of the computer programs. Test tokens composed of several sinusoidal frequencies (1 kHz, 3 kHz, and 5 kHz) of equal strength were analyzed by the computer programs and found to have the appropriate values for the various acoustic measures.

Results

Data were collapsed across repetitions of a given stimulus item, after which a repeated-measures analysis of variance (ANOVA) was used to determine significant spectral variation in the speakers' obstruent productions as a function of consonant type (when appropriate) and the speaking condition (without the pseudopalate, immediately following placement of the pseudopalate, and following a 20 minute period of sensory feedback with the pseudopalate in place). Dependent measures included the four spectral moments measures of spectral mean, spectral variance, spectral skewness, and spectral kurtosis). Results of significant *F*-tests include a measure of effect size, partial eta squared, or η^2 (the value of η^2 can range from 0.0 to 1.0, and can be considered a measure of the proportion of variance explained by a dependent variable when controlling for other factors). Greenhouse-Geisser adjustments were utilized to adjust *F*-tests with regard to degrees of freedom when significant deviations from sphericity were found. Moreover, pairwise comparisons for significant within-subject factors were done using General Linear Model repeated-measures contrasts; and comparison significance was determined using the appropriate *F*-tests.

Descriptive statistics (mean and standard deviation) for the dependent variables of spectral mean, spectral variance, spectral skewness, and spectral kurtosis can be found in Tables 1-3 for stop consonants and Tables 4-6 for fricative productions. Results from the repeated-measures ANOVA (*F*-ratios, probabilities, and effect sizes for significant main effects and interactions) that directly address the research questions of this study are included in the text below and are organized according to consonant type.

Stop Consonant Productions

Bilabial stops. For the bilabial stop /p/, a significant main effect in speaking condition was found for the dependent measure of spectral mean, $F(2, 38) = 7.71$, $p < .004$, $\eta^2 = .29$,

Table 1.

Spectral Measures of the Stop Consonants /p, t/ and /k/ for Speaking Condition 1

Stop Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/p/	*M*	3492	10.15	-1.17	-0.51
	SD	447	3.56	0.32	0.33
/t/	*M*	6020	2.88	0.17	0.60
	SD	744	1.03	0.66	1.74
/k/	*M*	5516	4.86	-0.34	-0.42
	SD	488	1.11	0.46	0.74

Note. Spectral mean measures in Hz; spectral variance in MHz.

Table 2.

Spectral Measures of the Stop Consonants /p, t/ and /k/ for Speaking Condition 2

Stop Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/p/	*M*	4143	9.57	-1.35	-0.01
	SD	604	1.98	0.39	0.66
/t/	*M*	5327	3.89	-0.30	0.66
	SD	638	1.62	0.70	1.01
/k/	*M*	4634	7.77	-1.17	0.16
	SD	719	2.90	0.49	0.50

Note. Spectral mean measures in Hz; spectral variance in MHz.

Table 3.

Spectral Measures of the Stop Consonants /p, t/ and /k/ for Speaking Condition 3

Stop Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/p/	*M*	4120	9.40	-1.27	-0.03
	SD	751	2.39	0.40	0.79
/t/	*M*	5625	3.91	-0.46	0.62
	SD	677	1.48	0.60	1.27
/k/	*M*	4948	6.79	-1.16	0.25
	SD	659	1.69	0.47	0.76

Note. Spectral mean measures in Hz; spectral variance in MHz.

Table 4.

Spectral Measures of the Fricative Consonants /s/ and /ʃ/ for Speaking Condition 1

Fricative Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/s/	*M*	7084	1.81	-0.73	1.48
	SD	806	0.67	1.17	2.60
/ʃ/	*M*	5532	2.36	0.35	0.61
	SD	474	0.65	0.41	0.95

Note. Spectral mean measures in Hz; spectral variance in MHz.

Table 5.

Spectral Measures of the Fricative Consonants /s/ and /ʃ/ for Speaking Condition 2

Fricative Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/s/	*M*	6468	2.44	-0.47	0.91
	SD	664	0.68	0.77	1.91
/ʃ/	*M*	5399	3.09	0.27	0.59
	SD	430	1.02	0.47	0.87

Note. Spectral mean measures in Hz; spectral variance in MHz.

Table 6.

Spectral Measures of the Fricative Consonants /s/ and /ʃ/ for Speaking Condition 3

Fricative Consonant		Spectral Mean	Spectral Variance	Spectral Skewness	Spectral Kurtosis
/s/	*M*	6766	2.31	-0.46	1.03
	SD	582	0.60	0.97	1.52
/ʃ/	*M*	5301	2.76	0.63	1.32
	SD	479	0.82	0.47	2.01

Note. Spectral mean measures in Hz; spectral variance in MHz.

and spectral kurtosis, $F(2, 38) = 5.62$, $p < .02$, $\eta^2 = .23$. As shown in Figure 1, subsequent within-subject contrasts indicated that the spectral mean of the /p/ production was significantly higher ($p = .006$) when the pseudopalate was in place (4143 Hz for condition 2 and 4120 Hz for condition 3) as compared to the without-pseudopalate speaking condition (3492 Hz). Significant differences in spectral kurtosis were also found between the without (-.51) and with-pseudopalate conditions (-.01 for condition 2 and -.03 for condition 3).

Lingual stops. Concerning the lingual stop articulations of /t/ and /k/, results of the ANOVA indicated a significant difference in spectral mean, $F(2, 38) = 19.35$, $p < .001$, $\eta^2 = .51$, and spectral skewness, $F(2, 38) = 30.44$, $p < .001$, $\eta^2 = .62$, as a function of speaking condition. For spectral mean, pairwise comparisons indicated significant differences between each of the three different speaking conditions. As shown in Figure 2, for both types of stop production the spectral mean decreased significantly ($p < .001$) when speaking with the pseudopalate in place. Although there was significant adaptation ($p = .001$) back toward baseline (condition 1) following 20 minutes of conversation (condition 3), there continued to be a significant difference ($p < .001$) between conditions 1 and 3. The means for the three speaking conditions were 5767 Hz, 4980 Hz, and 5286 Hz, respectively.

For spectral skewness, the stop productions exhibited a significantly higher ($p > .001$) degree of skewness in speaking conditions 2 and 3, with the pseudopalate in place. Although there was a small non-significant amount of adaptation toward baseline (condition 1), there remained a significant difference ($p > .001$) between conditions 1 and 3. The spectral skewness means for the three speaking conditions were -.08, -.74, and -.81, respectively. The ANOVA also revealed a significant interaction between stop type and speaking condition for the dependent measure of spectral variance, $F(2, 38) = 3.69$, $p < .05$, $\eta^2 = .16$. As shown in

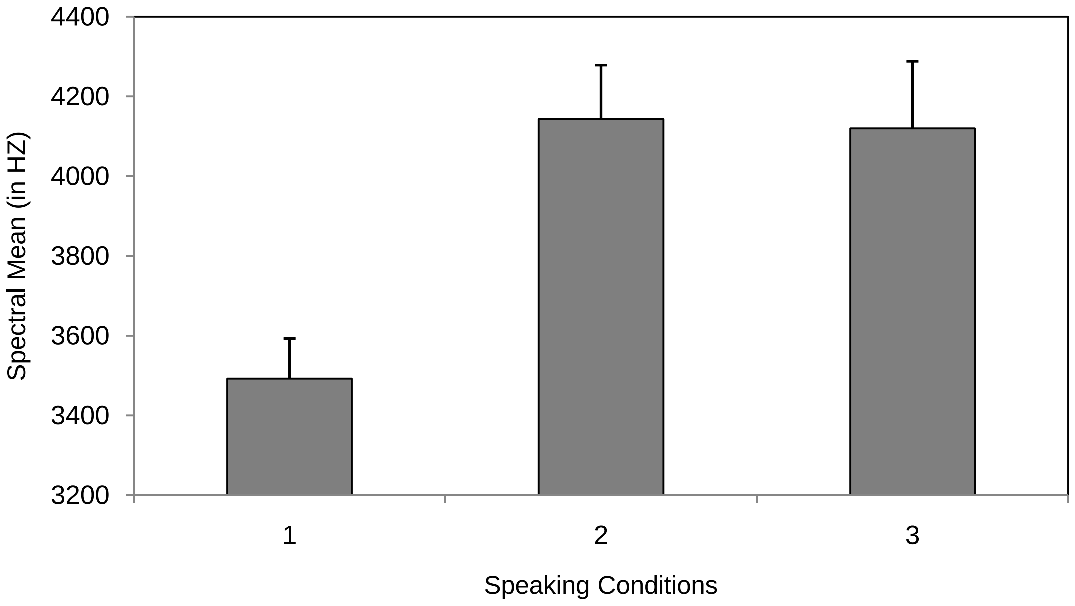

Figure 1.

Spectral mean of /p/ as a function of speaking condition.

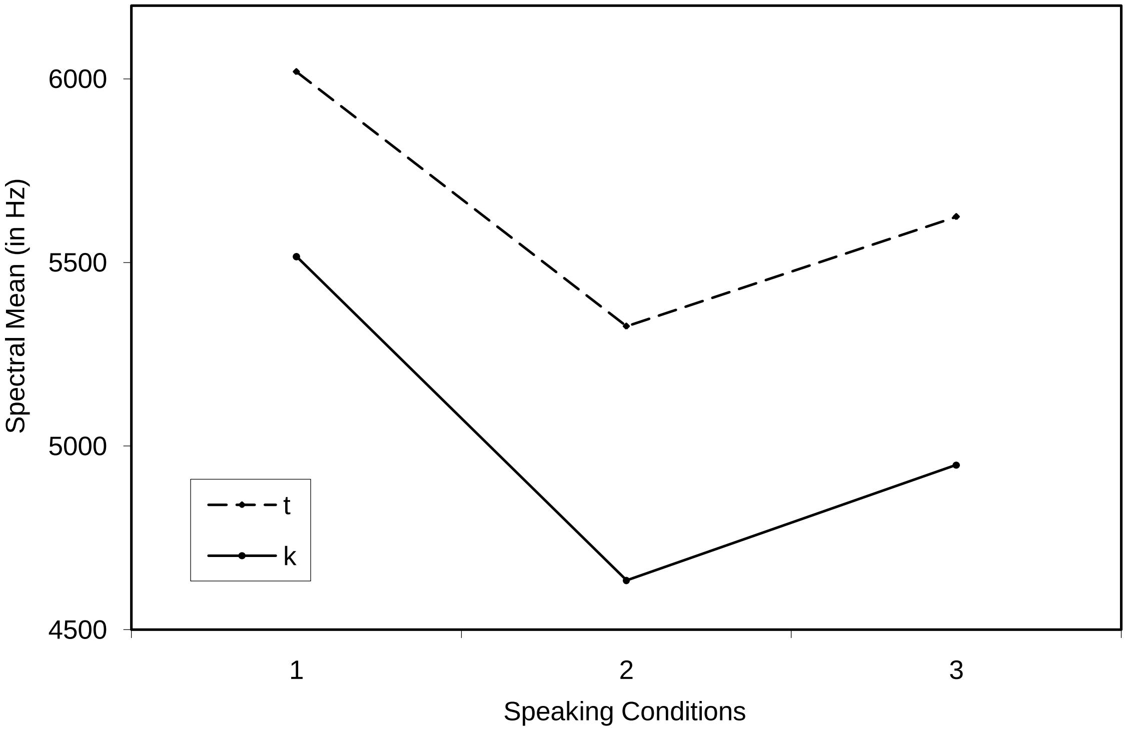

Figure 2.

Spectral mean of /t/ and /k/ as a function of speaking condition.

Figure 3, for both types of stops the spectral variance increased following the placement of the pseudopalate. However, after 20 minutes of conversation (condition 3), adaptation or a decrease of variance (-.98 MHz) toward speaking condition 1 only occurred for velar consonants (/k/), whereas alveolar consonants (/t/) showed a slight increase in variance (+.02 MHz). Variance means for both types of stop consonants across the speaking conditions can be found in Tables 1-3.

Fricative Consonant Productions

For the fricative articulations of /s/ and /ʃ/, results of the ANOVA indicated a significant difference in spectral mean, $F(2, 38) = 9.88$, $p < .001$, $\eta^2 = .34$, and spectral variance, $F(2, 38) = 16.07$, $p < .001$, $\eta^2 = .46$, as a function of speaking condition. As shown in Figure 4, pairwise comparisons indicated significant differences ($p < .01$) in spectral mean between the typical speaking condition and the speaking conditions with the pseudopalate in place. Although /s/ fricatives are trending toward condition 1, when collapsed across both types of fricatives the overall difference is not significant. In addition, the fricative type by speaking condition interaction is also not significant. The means for the three speaking conditions were 6308 Hz, 5934 Hz, and 6033 Hz, respectively.

For spectral variance, the fricative productions exhibited a significantly higher ($p > .001$) amount of variance in both speaking conditions with the pseudopalate in place. Although there was a small non-significant amount of adaptation toward baseline (condition 1), there remained a significant difference ($p > .001$) between conditions 1 and 3. The means for spectral variance across the three speaking conditions were 2.08 MHz, 2.77 MHz, and 2.53 MHz, respectively.

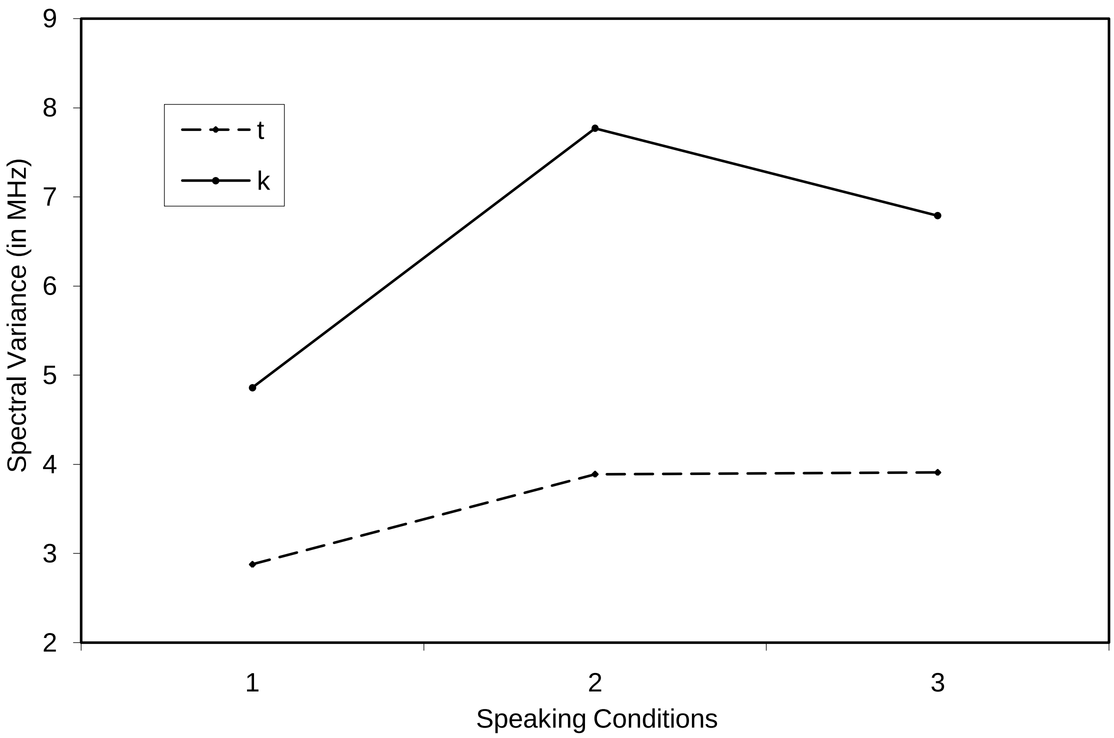

Figure 3.

Spectral variance of /t/ and /k/ as a function of speaking condition.

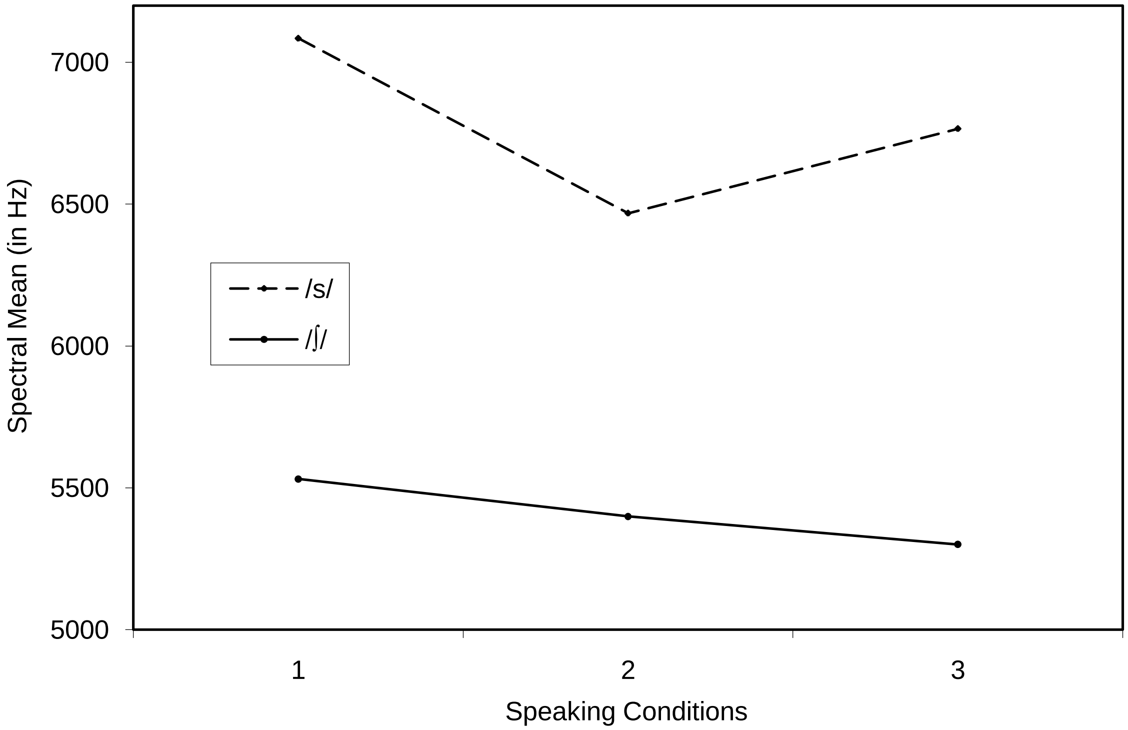

Figure 4.

Spectral mean of /s/ and /ʃ/ as a function of speaking condition.

Discussion

Findings from this study indicate that the placement of a pseudopalate does result in a significant disturbance of some of the spectral characteristics of the voiceless obstruents /p, t, k, s/ and /ʃ/. Statistical analyses of bilabial stop /p/ productions indicated a significant increase in the spectral mean immediately after pseudopalate placement, and then a significant decrease in the mean after a 20 minute practice period. Although there was significant adaptation, spectral mean values remained significantly different than those found without the pseudopalate. In terms of adaptation, EPG wires exiting the mouth may have interfered with the speakers' ability to create a complete stop occlusion, thus causing an increase in the mean and preventing complete articulatory compensation. These results indicate that the spectral mean of /p/ was significantly influenced by pseudopalate placement, and that /p/ productions only minimally trended back to their original mean value.

Analysis of the lingual stop productions (/t/ and /k/) found that all spectral measures except kurtosis were significantly affected by pseudopalate placement. For both types of stop articulation, the spectral mean for speaking condition 2 (immediately following pseudopalate placement) significantly decreased from the mean of condition 1 (without the pseudopalate), and then significantly increased in condition 3 (following a 20 minute practice period). This decrease might have been caused by speakers attempting to compensate for the presence of the pseduopalate by articulating the /t/ and /k/ further back in the oral cavity. Forming these phonemes further back would have lengthened the frontal cavity, thereby affecting the resonance of /t/ and /k/. A significant interaction between stop type and speaking condition was found for the measure of spectral variance. Both types of stop consonant /t/ and /k/ demonstrated a significant increase in spectral variance immediately after pseudopalate placement. However following 20 minutes of conversation, the spectral variance of /t/

continued to increase, while /k/ began to decrease towards its original value. This difference in adaptation may be due to the place of articulation for /t/ and /k/. Alveolar stop consonant productions (/t/) might encounter more interference from the pseuodpalate than velar stops (/k/) because of the protrusion of the alveolar ridge into the oral cavity, a location where /t/ is usually articulated. It is possible that the relatively confined space near the alveolar ridge does not allow for the complete occlusion of the vocal tract in order to articulate a crisp production of /t/. The lack of a complete closure may have caused a diffusion of the spectral energy, thereby increasing the spectral variance.

Fricatives /s/ and /ʃ/ followed a trend similar to that of the lingual stops in that the mean values for the measures of spectral mean and spectral variance were significantly influenced by pseudopalate placement. For /s/ and /ʃ/ the spectral mean was decreased immediately following pseudopalate placement, this suggests that the front resonating cavity may be longer or larger than is typical. The cause of this may be that speakers moved their articulations back a little, particularly for /s/. Deepening of the lingual groove and increased lip rounding for /s/ in response to the thickness of the pseudopalate and the protruding wires may have also contributed to the decrease in spectral mean. Similar to the lingual stop productions, the fricative productions exhibited an increase in spectral variance when the pseudopalate was in place. The structural perturbation of the pseudopalate may have caused the articulatory gap through which the fricative turbulence was created to be less rigidly and accurately sustained, thereby causing diffusion in the spectral energy.

While the results of this study indicate that the presence of the pseudopalate altered speakers’ articulation, some of the spectral measures show that an adaptation effect began to occur. An example of this phenomenon is illustrated by the spectral mean values for /t, k/ and

/s/ which decreased immediately after pseudopalate placement and then increased again following a 20 minute practice period. Means which began to return to prior values suggest that speakers' productions started to approximate their typical speech following a practice period.

Although the participants in the current study did not demonstrate complete adaptation to the pseudopalate, the results are comparable to the findings of other researchers. An artificial palate study performed by Baum and McFarland (1997) used acoustic and perceptual analyses to determine whether intensive practice of /s/ would result in adequate adaptation to palatal modification. Acoustic analyses revealed lower spectral means in the palate condition than in the normal condition. Moreover, the mean values increased over time and revealed improvement, but not complete adaptation. The spectral mean trends noted in Baum and McFarland's study correlate with the trends found in the current study, wherein palate placement resulted in a significant disturbance of speakers productions.

A thesis by Andrea Weaver (2005) also provides data which support the ability of individuals to adapt to oral perturbations. This study investigated the effect of lingual magnets on fricative production using acoustic and perceptual analyses. Results indicated an increase in spectral mean and variance for /ʃ/ immediately following placement of the magnet. However, after 5 minutes of conversation, no significant differences were observed in any spectral measure for /s/ or /ʃ/. In comparison to the current study, the spectral measures which increased and then returned to normal indicate a relatively quick adaptation after just 5 minutes. Spectral measures of the current study did not return to normal as in the Weaver study; however, they both support the theory that adaptation can occur in the presence of an oral device. The difference in mass between a lingual pellet and pseudopalate probably accounts for the differences observed between the findings reported by Weaver and the current study.

This study found that the placement of an artificial pseudopalate resulted in the statistically significant disturbances of some spectral characteristics (mean, variance, skewness, and kurtosis) of a small group of voiceless obstruents. However, it is unknown whether these disturbances are significant enough for listeners to perceive. A perceptual component should therefore be added in future studies in order to determine whether listeners can perceive a significant articulatory difference between the three speaking conditions.

There are several limitations to the methodology used in this study. The short 20 minute practice period with the pseudopalate might have been an insufficient amount of time to allow for adaptation to occur. Similar to Baum and McFarland (1997), in order to determine the amount of time needed for full adaptation, a systematic study of many different adaptation periods (e.g., 0, 15, 30, 45, 60 minutes) may be necessary. This idea also coincides with McFarland et al., 1996, who found that a 15 minute practice period was an insufficient amount of time to allow for complete adaptation to an oral perturbation. An intensive practice period similar to that used by Aasland et al., (2006) may also have improved the likelihood of successful and complete adaptation. Another key point is that the stimulus sentences, *the boot on top is packed to keep* and *the boy gave a shout at the sight of the cake*, provide a somewhat limited and contrived context from which the data were collected. A longer phrase or paragraph may have strengthened the auditory feedback loop through which speakers monitor their own speech productions, as well as provided a more naturalistic context from which the data could have been drawn.

The population targeted by this method of EPG technology is also important to consider. The EPG is designed in part to help children with articulatory disorders who have not benefitted from traditional therapy techniques. The current study focuses on the productions of adult speakers who have highly solidified or habitualized articulatory patterns. Therefore, the articulatory adaptation trends noted by this study may not generalize to children. Future adaptation studies should assess sample populations of children because their speech productions are more variable and much more easily influenced. It would also be interesting to investigate the adaptation abilities of individuals with a history of articulation disorder.

Additionally, the stimulus phonemes limited to the context of the initial position provide a very narrow view concerning the effects of a pseudopalate on articulation. Examining obstruents /p, t, k, s/ and /ʃ/ in all positions is another direction of possible study. A further constraint of the current study is that each phoneme was isolated to a one word context (*packed, top, keep, sight,* and *shout*) with no attention given to the vowels subsequently following each phoneme. Future research should also consider a variety of vowel contexts following each phoneme of interest.

Conclusion

The spectral analysis conducted in this study indicated that the placement of a relatively thin pseudopalate resulted in a significant disturbance of the spectral characteristics of speakers' productions of the voiceless obstruents /p, t, k, s/ and /ʃ/. Although participants began to demonstrate an adaptation to the interference caused by the pseudopalate after 20 minutes of practice with the device, for several of the spectral measures their articulations remained significantly different than the typical patterns of production displayed when speaking without the pseudopalate in place. It is unclear from this study if additional practice time with the pseudopalate would eliminate these differences or if such differences are even perceptually relevant. Despite the inherent limitations of this study the results provide a foundation for further research regarding the effect an artificial pseudopalate might have on typical patterns of speech articulation and how speakers might adapt to the pseudopalate after a short period of practice.

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Appendix

Informed Consent Document

The purpose of this research study is to create a normative database of tongue contact patterns during speech. It is being conducted by Dr. Christopher Dromey and Dr. Shawn Nissen, who are faculty members in the Department of Communication Disorders at Brigham Young University, as well as by Dr. Samuel Fletcher, an adjunct faculty member in the same department. You were selected for participation because you are a healthy young adult speaker of Standard American English with no history of speaking abnormalities, hearing problems, jaw problems, or serious dental abnormalities.

The first session will involve reading a passage and repeating several sentences into microphone. These recordings will be rated by experienced listeners, and a subset of the speakers will be invited to participate in the second phase of the study.

The second session for those who are selected by the expert listeners as the most articulate speakers will include a brief examination of your mouth, followed by the making of an impression of your upper teeth and palate. This impression is taken with a water-based molding material, which is commonly used in dentistry. The impression will be used to make a pseudopalate, which is a mold of your palate, formed with orthodontic plastic.

You will subsequently be asked to make a visit to the speech research lab, located in Room 106 of the Taylor Building. A flexible printed circuit will be attached to the pseudopalate, which will allow the electronic detection of the contact between your tongue and the pseudopalate as you speak. During this visit to the lab you will be asked to speak some words and sentences while wearing the pseudopalate that was made to fit your dental impression. You will be the only speaker to ever use this pseudopalate, which will be cleaned in a sterilizing solution before you use it.

There are no known risks associated with participation in this study. Electronic pseudopalates have been used for a number of years in the speech pathology community without any reports of adverse events. The new instrument is simply a more modern and sensitive version of the same technology that has helped clarify the patterns of tongue contact in normal and disordered speech in clinical settings across the continent. It may take several minutes for you to adjust to the presence of the device in your mouth, but it will not affect your breathing or the way you speak. There are no specific benefits to you. Your participation in this study will help in the generation of ideal tongue contact patterns, which my help in the treatment of individuals with speech problems.

Participation in this research is completely voluntary. You have the right to refuse to participate and the right to withdraw at any time without prejudice. Strict confidentiality will be maintained. No individual identifying information will be disclosed in any presentations or publications based on this work without your prior written consent.

If you have any questions regarding this research project, you may contact Dr. Christopher Dromey, 133 TLRB, BYU, phone (801) 422-6461, e-mail dromey@byu.edu. If you have questions regarding your rights as a participant in a research project you may contact Dr. Renea Beckstrand, IRB Chair, 422-3873, 422 SWKT, renea_beckstrand@byu.edu.

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

Research Participant Date