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THE EFFECT OF A LINGUAL MAGNET ON FRICATIVE PRODUCTION: AN
ACOUSTIC EVALUATION OF PLACEMENT
AND ADAPTATION

by

Andrea Weaver

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 Audiology and Speech-Language Pathology

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

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As chair of the candidate's graduate committee, I have read the thesis of Andrea Weaver in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

THE EFFECT OF A LINGUAL MAGNET ON FRICATIVE PRODUCTION: AN ACOUSTIC EVALUATION OF PLACEMENT AND ADAPTATION

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Master of Science

Much of speech kinematics research is conducted by attaching a device to the articulators. However very little research has been conducted to determine what influence these devices may have on the perceptual and acoustic characteristics of speech. This study examined the effect of placing a small magnet on the tongue of ten normal adult speakers while reading a sentence containing /s/ and /ʃ/ in initial, medial and final position. Two different placements of 10 and 15 mm from the tip of the tongue were analyzed. Data were taken before magnet placement, immediately after magnet placement, after 5 minutes of conversation, and after an additional 10 minutes of conversation. The acoustic output was analyzed using spectral moments analysis (spectral mean, variance, skewness, and kurtosis). Changes in spectral mean and variance were found for /ʃ/ as a result of magnet placement, which was characterized by

an interaction effect between condition and the word position of the target fricative. In addition, significant changes in spectral mean were found for /s/ and /ʃ/ as a result of magnet position. Although results from the present study indicated that there were some acoustic changes in fricative productions with a marker attached at midline, the spectral changes were not consistent or pervasive, and speakers were able to adapt to the presence of the magnet in a relatively short amount of time.

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Introduction

The specific articulatory processes that result in human speech have intrigued researchers for many years. Speech is communicated from speaker to listener primarily through sound waves. This acoustic speech signal is created through a combination of complex steps that result in the signal we perceive as meaningful communication. These steps include the movement of the articulators to help shape the acoustic realization of different speech sounds.

Due to its flexibility, the tongue is directly involved in the production of the majority of human speech sounds (Peña-Brooks & Hedge, 2000). As Kent (1997) describes, “It can bunch, protrude, retract, wag from side to side, curl up its tip, form a midline groove, and explore the oral cavity within which it resides” (p. 176). In addition to its flexibility, the tongue’s central location allows it to efficiently shape the sound wave as air passes through the vocal tract.

Thus, the focus of many studies has been to accurately describe the movements of the tongue during the process of speech production. However, monitoring the movements of the tongue is somewhat difficult. Articulation of the tongue is often hard to visualize because of its location in the vocal tract. In addition, the dynamic and often transient nature of many articulatory movements is difficult to track without the aid of sensitive instrumentation.

Traditionally, researchers have used a variety of ways to investigate the physiological role of the tongue during the production of speech. Many studies have sought to understand speech through the monitoring of muscle contractions, acoustic analysis, and by directly tracking the movement of the tongue. To monitor articulatory

movements, researchers have historically used a variety of tools such as palatometers (Fletcher, McCutcheon, & Wolf, 1975; Hardcastle, 1972; Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989; Palmer, 1973), x-ray microbeam (Fujimura, Kiritani, & Ishida, 1973), ultrasound (Sonies, 1991; Stone, 1990; Stone, Faber, Raphael, & Shawker, 1992), and electromagnetic articulograph systems (Perkell et al., 1992; Schonle et al., 1987).

Although these instruments have provided valuable articulatory data, one drawback is that many of these techniques involve attaching a traceable device, such as a magnet or pellet to the articulator of interest. Some studies have shown that introducing devices to the articulatory system may cause speakers to produce speech in an unnatural manner (McFarland, Baum, & Chabot, 1996). Ichikawa, Komoda, Horiuchi, and Matsumoto (1995) indicated that the influence of alterations in the oral environment affected the timing of articulation in a group of subjects. Even devices not directly attached to the tongue, such as the pseudopalate, can interfere with speech. In one study, Palmer (1979) demonstrated that the presence of dental prostheses caused significant articulation errors.

Despite evidence indicating that introducing foreign objects, such as magnets or prosthetic devices, to the oral environment may have an effect on articulation, research has also shown that the articulatory system can adapt to such changes. One common example is found after the application of orthodontia. When individuals are initially fitted with braces or retainers, their speech is distorted due to the resulting changes in the oral cavity. However, speech generally returns to normal after a period of adjustment. Formal studies involving dental appliances (Hamlet, 1973) and bite blocks (Baum,

McFarland, & Diab, 1996; McFarland & Baum, 1995) have shown that such adaptation can occur in a relatively short amount of time. This adaptation effect is in part attributed to a speaker's auditory feedback loop (McFarland & Baum, 1995). If prosthesis wearers receive auditory feedback that their speech sounds unnatural, they will generally modify their articulation to compensate for the device. Some research has shown that with many types of orthodontic devices, speakers can modify their articulatory patterns to produce speech that is perceptually similar to their speech without the device in place (Ichikawa et al., 1995). However, it is important to note that the ability of speakers to adapt their speech in such a manner is highly dependent on the size, shape, and location of the device.

In light of the research mentioned above, it is logical that researchers would examine the effect of devices used to track movement on normal articulation and a speaker's ability to adapt to such devices. Nevertheless, Weismer and Bunton (1999) noted that there were surprisingly few formal evaluations of the potential influence of perioral and intraoral devices on speech production behavior. Thus, the purpose of this study was to examine the effect of attaching a small tracking device to regions of the tongue on the production of running speech and the rate at which speakers are able to adapt to the presence of the device. Specifically, this study focused on the effect of attaching a small magnet to the tongue on the spectral characteristics of two fricatives commonly found in American English, /s/ and /ʃ/.

Review of Literature

The Tongue

The tongue plays a central role in the physiological tasks of mastication, swallowing, and verbal communication. Its central position in the vocal tract is an ideal location to alter the shape and length of the resonating cavities of the mouth during speech. For many sounds, the tongue acts as an air stream valve by approximating or contacting other articulators. This valving action is essential for the production of speech sounds such as stops, fricatives, and affricates. For these reasons, some researchers consider the tongue to be the predominant articulator for speech (Ferrand, 2001).

Areas of the tongue can be anatomically classified into several distinct sections. The apex is the anterior portion of the tongue, the blade is posterior to the tip and lies under the alveolar ridge when the tongue is at rest, and the section posterior to the blade is often referred to as the dorsum. Another major landmark of the tongue is the median fibrous septum, which runs longitudinally along the length of the tongue, dividing it into approximately equal left and right halves.

The tongue is made up of numerous independent muscles that intertwine in a complex manner, resulting in extensive mobility, flexibility, and speed of movement. These muscles are commonly divided into two distinct categories: extrinsic and intrinsic. The extrinsic speech muscles have one attachment in the tongue and one attachment to anatomical structures outside of the tongue. These muscles are primarily responsible for positioning the tongue in different locations within the oral cavity. The intrinsic lingual muscles have all attachments within the tongue and serve to make fine adjustments to its position and shape (Ferrand, 2001). Due to its self-supporting muscle mass, the tongue is

also sometimes referred to as a “muscular hydrostat” (Kent, 1997). There is no bone or cartilage in the tongue, therefore structural support comes from the contraction of selective tongue muscles. When one portion of the tongue contracts, the resulting tension provides a solid foundation for another portion of the tongue to perform its movement. The result is that different areas of the tongue can function semi-independently of each other (Ferrand, 2001).

Areas of the tongue can move in different ways. Hardcastle (1976) explains that the tip and blade can navigate in a horizontal anterior-posterior plane and in a vertical upward-downward plane. The tongue body can also move in these two planes, as well as adopt a convex or concave shape in relation to the palate. The tongue can assume this shape throughout its length, which results in a groove or sulcus along the median fibrous septum. In addition, the dorsum can also either be spread or tapered (Ferrand, 2001).

Techniques Utilized to Monitor Articulation

Motor command. There are a variety of ways to study the physiological activity of the tongue that is associated with sound production in human speech. Electromyography (EMG) is one technique that has been developed to monitor the motor commands received by the muscles of the tongue. Motor commands are the neural impulses that are transmitted to the muscles, resulting in contraction. In EMG, electrodes are attached to the muscle or muscles of interest. These electrodes register and record the electrical impulses that cause the muscles to contract. Surface, needle, hooked, or micro electrodes can be used to gather information regarding individual and multiple motor units, as well as overall muscle activity. However, EMG is most useful when measuring a small group of bundled muscles (Kent, 1997).

Acoustic analysis. Acoustic analysis is another method by which the articulation of speech can be studied. Stetson (1928) wrote that “speech is movement made audible.” In other words, the end product of the movement of the articulators during speech is an acoustic realization, which listeners perceive as sound (Kent & Read, 2002). The acoustic investigation of speech articulation involves drawing inferences about the movements of the articulators from examination of the acoustic waveform. However, the indiscrete and quickly decaying nature of speech often makes it challenging to quantitatively analyze. As Tasko and Westbury (2002) report, “establishing and evaluating approaches for movement unit definition has both theoretical and practical implications. The manner in which the speech units ... unfold in time is at the heart of many theoretical discussions on speech production” (p. 130).

Acoustic analysis of speech has been aided in recent years by spectral moments analysis. This type of analysis examines the spectral characteristics of discrete time segments of the speech signal in terms of statistical moments (i.e., mean, variance, skewness, and kurtosis). In the first spectral moment the average energy distribution of a Fast Fourier Transform (FFT) power spectrum is examined. The FFT is a process by which a temporal waveform, such as speech, is described as frequency components of varying amplitudes. The second moment gives the variability of frequencies over which the power spectrum is spread (Nissen, 2003). The skewness of the spectrum distribution is examined in the third spectral moment. If the third spectral moment is positive, it indicates that the median component of the FFT spectrum has a lower frequency than the mean. The kurtosis or “peakedness” of the energy distribution is described by the fourth moment. A high value indicates well-defined spectral peaks, and a low kurtosis value

indicates a flat distribution (Jongman, Wayland, & Wong, 2000).

Previous studies have primarily used spectral moments analysis to examine the acoustic structure of obstruent speech sounds (e.g., Forrest, Weismer, Hodge, Dinnesen, & Elbert, 1990; McGowan & Nittrouer, 1988; Nissen, 2003). These studies have often sought to classify obstruent articulation or study the development of stop and fricative production. Specifically, several of these studies investigated whether the place of articulation of stop burst and fricative speech sounds could be statistically differentiated based on the patterns of spectral energy in their noise segments (Forrest, Weismer, Milenkovic, & Dougall, 1988; Jongman et al., 2000).

Forrest et al. (1988) was one of the first studies to use spectral moments analysis to classify differing obstruent speech segments. Spectral data were extracted from a series of 10 ms analysis windows beginning at the stop burst and continuing to the start of the following vowel. The first four spectral moments were computed from each FFT using both linear and Bark transformed spectra. In the Bark transformation a linear frequency scale is transformed to an auditory scale that more closely matches human hearing perception (Zwicker & Terhardt, 1980). Using the moments calculated from the linear spectra, 92% of the voiceless stops were classified correctly, regardless of gender. Using Bark transformed spectra, the classification results improved to an accuracy of 98%.

Jongman et al. (2000) described the acoustic characteristics of voiceless and voiced fricatives in American English. The researchers were interested in finding the most accurate way to classify the place of articulation of fricative segments of speech. They utilized a variety of static (spectral peak location, spectral moments, F2 onset

frequency, noise amplitude, noise duration) and dynamic (relative amplitude and locus equations) acoustic measurements. The authors found that spectral peak location and variance distinguished all four places of articulation for fricatives, regardless of variation in speaker, vowel context, or voicing.

Spectral moments research has also been used to study typical vs. disordered phonological development in children (Forrest et al., 1990; Miccio, 1995). Nittrouer (1995) utilized spectral moments analysis to investigate the theory that children's articulatory gestures are not as precisely specified as those of adults, and that some patterns reach adult-like precision at earlier ages than others. The author found that a significant difference in the magnitude of vowel-context effects was observed for /k/, suggesting that children's place of velar closure was more influenced by anticipatory vowel production than adults'. In addition, Nittrouer found that the difference in the first spectral values (mean) between /s/ and /ʃ/ was larger for adult speakers than for children, yet the differences between /t/ and /k/ were relatively similar. Nittrouer interpreted this finding as support for the conclusion that in terms of the first spectral moment the child speakers were continuing to "fine tune" their sibilant fricative articulations toward a more adult-like contrast.

Articulatory Contact Tracking Systems

Palatography is a method that can give precise information about tongue-palate contact. Historically researchers used powder dusted onto the patient's hard palate to identify the place of lingual articulatory contact (Rousselot, 1924). More recently Electropalatography (EPG) has been used to describe how the tongue contacts the palate during speech. Although different EPG systems exist (Fletcher et al., 1975; Fujimura,

Shibata, Kiritani, Shimada, & Satta, 1968; Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989; Kuzmin, 1962; Kydd & Belt, 1964), most operate according to the same basic principles. EPG generally uses molded palates containing electrodes connected by thin wires that exit the mouth at the corners. When the tongue makes contact with the palate it completes an electrical circuit that connects a “sending” to a “receiving” electrode (Baken & Orlikoff, 2000). The timing and placement of each contact is then recorded. This system allows a series of movements to be recorded, rather than being limited to just one articulatory movement. However, the limitations of EPG include expense, limited ability to detect posterior palatal and linguavelar contact, and possible interference of the device with articulation (Baken & Orlikoff, 2000).

Imaging Systems

Over the past few decades medical technology has developed imaging techniques such as radiographic, magnetic resonance imaging, and ultrasound (Kent, 1997). In ultrasonography, a specialized transducer is placed in close contact with the region to be analyzed. This transducer emits sound waves that pass through the body. As the waves encounter boundaries between the tissues, they are reflected back.

Ultrasonography is ideal for speech research because it can examine the speech movements without directly interfering with articulation. However, its expense and lack of availability prohibits many professionals from accessing the technology. Despite this drawback, ultrasound has been used to investigate lingual movements in swallowing and speech (Sonies, 1991; Stone, 1990), cross-sectional tongue shapes during fricative production (Stone et al., 1992), and various types of vocal tract imaging (Stone, 1991).

Kinematic Articulator Tracking Systems

Another method of analysis utilizes traceable devices attached directly to the articulators. Several common articulatory tracking devices are the strain gauge, x-ray microbeam, Electromagnetic Midsagittal Articulometer, and magnet tracking systems. The strain gauge is a device used to measure structural movement, such as lip and jaw movements. The basic configuration usually involves gauges mounted on a flexible metal strip anchored at one end to form a cantilever. The free end is attached to the lip or jaw and as the free end moves, it bends the metal strip. This bending action causes measurable compression on a convex and concave surface (Baken & Orlikoff, 2000). To ensure accurate measurement of the articulators during speech, the head of the speaker is usually held relatively still in some sort of stabilization device (Abbs & Stivers, 1978; Sussman & Smith, 1970). The loading factor, or force required to bend the metal strip, is a key issue in utilizing the strain gauge. If too much force is applied, the soft tissue will be deformed and the area the strip is fixed to will not move in a natural manner, resulting in inaccurate measures.

The x-ray microbeam system (XRMB) is another well-known articulatory tracking device. When using the XRMB, researchers attach spherical gold pellets to the articulators of interest to track their movement during speech. These gold pellets are 2-3 mm in diameter and are attached to threads so they can be retrieved in case of aspiration. During articulation, a narrow electron beam is passed through a pinhole aperture to image the movement patterns of the pellets. The x-ray beam path is adjusted based on high-speed computations that predict the expected locations of each pellet. Data collected from the XRMB have been compiled into a publicly available Speech Production

Database.

A device which avoids the radiation used in the XRMB is called the electromagnetic midsagittal articulography (EMMA) system (Hixon, 1971; Byrd, Browman, Goldstein, & Honorof, 1999). The EMMA system works by attaching transducer coils to the oral articulators in the midline plane. Transmitter coils are then mounted on a frame that fits on the head of a speaker. These transmitter coils emit alternating magnetic fields that cause the transducers to produce alternating voltages. Lead wires connect the transducers to receivers and the output voltages give transducer position as a function of time (Perkell et al., 1992).

Another tracking system available for speech research is the modified JT-3, a head-mounted magnet tracking system developed by BioResearch Associates. It was originally designed for dentists to examine jaw movements, but the manufacturers modified it to track tongue movements. The modifications included using a smaller magnet (1.2 mm thick, 7 mm in diameter) and separate analog output for the three measured planes: posterior, inferior-superior, and lateral displacement. The JT-3 has been used recently to track tongue movement in bilingual speakers (Wheeler, 2004).

Adaptation Effect

Humans are extremely skilled at adapting to new circumstances, including speech adaptation to alterations in the oral environment (McFarland et al., 1996). Several studies (Kent, Martin, & Sufit, 1990; McFarland & Lund, 1995; Smith, 1992) have explored the link between somatosensory and/or auditory feedback and central control signals; however, the specific pathways involved have not yet been positively identified (McFarland et al., 1996). Researchers theorize that when perturbations are introduced

into the speech system, humans use sensory feedback to form motor control programs that are appropriate for the changed environment (McFarland et al., 1996).

Studies investigating the adaptation rate for artificial palates have reported mixed results. A study conducted by Flege (1986) found that after a five minute time period an artificial pseudopalate did not perceptually interfere with speech production in a significant manner. However, other studies involving artificial palates have found this adaptation period to be lengthier (Hamlet & Stone, 1974).

Interestingly, some studies (Gay, Lindblom, & Lubker, 1981; Kelso & Tuller, 1983; Lindblom, Lubker, & Gay, 1979) have found that the adaptation period for a bite-block may actually be longer than the adjustment period for some types of palatal appliances. McFarland et al. (1996) conducted a study that evaluated speakers' ability to adapt to both thick (6mm) and thin (3mm) artificial palates and a bite block. Using perceptual ratings and spectral moments analysis the researchers found that speech sounds of different phoneme classes were differentially impaired, with the production of the fricative /s/ being more significantly influenced than other sounds by the artificial palates and fixation of the jaw with a bite-block. The authors hypothesized that the production of the alveolar fricative (/s/) was differentially affected because it requires greater articulatory precision than the other sound classes studied (vowels and stops). The researchers also noted that small changes in sibilant articulation translated into significant acoustic changes. They also found evidence of perturbation on stops with the artificial palate in place. However, they did not draw firm conclusions as to the specific manner in which stops were affected, but indicated that stops are more affected than vowels and less affected than sibilants. The authors noted that speech compensation for

some speech sounds improves over time (15 minutes in their study). McFarland et al. also concluded that different speakers have differing levels of ability to adapt to the changes in oral environment.

Although numerous studies have focused on speech perturbation and adaptation with artificial palates and bite blocks, surprisingly little research has focused on the effect of attached tracking devices commonly used to measure articulatory movement on speech articulation. Weismer and Bunton (1999) pointed out that even though the XRMB tracking system is utilized for speech research, the potential effects of lingual pellets or coils on speech had never been formally evaluated. Thus, their study addressed possible differences in acoustic output and listener judgments for utterances produced by speakers with and without pellets (XRMB system) attached to the tongue and other articulators. The acoustic measures chosen were segment durations and vowel formant frequencies, formant trajectory measures, and spectral moments for fricatives. The study found that some individuals exhibited slightly higher spectral means in the “pellets-on” condition. However, these effects were not consistent across subjects and there were no consistent segment level effects for specific sound types.

Weismer and Bunton (1999) studied the potential effects that one system, the XRMB, may have on speech. In their conclusion, the authors noted that there were surprisingly few formal evaluations of the potential influence of perioral and intraoral devices on speech production behavior. As there are many different types of articulator tracking systems, and different types of devices attached, it is evident that more research is needed to examine what effects different traceable devices might have on speech.

Specific Purposes of Study

Thus, the specific purposes of this study were to investigate the following research questions:

1. Does the placement of a traceable device, such as the type of magnet used in a modified JT3 system, result in significant disturbance in the spectral realization of fricatives /s/ and /ʃ/? If so, in what manner does the magnet alter the spectral characteristics of these specific speech sounds?
2. Does placement of the magnet in different anterior to posterior regions of the tongue (10 or 15 mm) differentially affect the spectral realization of fricatives?
3. Do the speakers in this study exhibit an adaptation to the attached magnet after speaking with the device for a short period of time (5 – 10 minutes)?

Method

Participants

Ten college-aged native speakers of English participated in this study on a volunteer basis. The participant group contained an equal number of male and female participants. The individuals were not paid for their participation and were naïve to the exact purposes of the study. Participants reported that they had no history of a speech, language, or hearing problem.

Procedures

Prior to testing, each participant read and signed an Informed Consent Document approved by the Brigham Young University Institutional Review Board for Human Subjects Research (Appendix). At the beginning of each test session the participants were instructed to read the following elicitation sentence three times without an attached magnet: “*Allison had to miss a sunny vacation at Shellfish Bay.*” This sentence was chosen because it includes target real words containing the phonemes /s/ and /ʃ/ in initial, medial, and final word positions. Subsequently, a small magnet (1.2 mm thick, 7 mm in diameter) was attached to each speakers’ tongue at 10 or 15 mm (measuring from the tongue tip to anterior edge of magnet) along the medial septum using dental adhesive. The participants then read the target sentence 3 more times with the magnet in place. Thereafter, with the magnet still in place, the participant engaged in 5 minutes of casual conversation with the experimenter. This period of conversation was included to give participants time to adapt to the magnet. After the five minutes of conversation, the participants were once again instructed to read the target sentence three times. The speaker was then engaged in an additional 10 minutes of conversation and subsequently

asked to read the target sentence three more times.

Two different recording sessions were required for the different magnet placements of (i.e., 10 or 15 mm) from the tip of the tongue. The order of the placements for each participant was randomly determined to reduce sequencing effect. In addition, the participants' two sessions were conducted on different days to ensure that any sensation from the previous magnet position did not interfere with speech on subsequent placements.

Recording

Speech samples were recorded online to computer in a sound-treated room. More specifically, a low impedance dynamic microphone (DPA 4011) and an analog/digital converter (Apogee Mini-me) were used to record the participants' productions. The microphone was affixed to a mic-stand and placed approximately 15 cm from the speaker's lips during recording. The speech tokens were sampled at a rate of 44.1 kHz and low-pass filtered at 22.05 kHz with a quantization of 16 bits.

Segmentation

Segmentation of the fricative targets was conducted using waveform display assisted by spectrographic inspection (Audigy, 2003). The fricative onset was characterized by a rapid increase in zero-crossings and/or spectrographic identification of high frequency energy, whereas the offset was the intensity minimum prior to the onset of vowel periodicity and/or absence of high frequency energy (Jongman et al., 2000). In addition, all segmentation points were verified by auditory monitoring. Segmentation values were then recorded into a text file (in ms) and later checked and corrected (and then re-checked) using a MATLAB program that displayed the segmentation marks

superimposed over a display of the token's waveform. In addition, to test for segmentation accuracy and reliability, randomly chosen tokens ($N = 100$) were independently analyzed by a second individual. The fricative boundary measurements were subsequently correlated ($r = .98, p < .001$) to the original segmentation values extracted for these same tokens.

Acoustic Analysis

Acoustic analysis followed procedures outlined in previous research examining the acoustic properties of voiceless obstruents (i.e., Forrest et al., 1988; Jongman et al., 2000; Nissen, 2003; Nittrouer, 1995). A duration measure was computed for each fricative segment from the raw time points (in ms) extracted during segmentation. In addition, the first four spectral moments (mean, variance, skewness, and kurtosis) were calculated for each obstruent segment.

Spectral Moments Analysis

For the fricative tokens, a 40 ms Hamming window located at the middle of the segmented portion of frication was utilized. Moments were only calculated for fricative tokens that were at least 80 ms in duration (following this rule, 3 tokens were eliminated from the analysis). Each window interval was then pre-emphasized by first-differencing. Though the need for pre-emphasis is minimized when analyzing voiceless sounds, it was determined that such a procedure was necessary to more effectively compare subsequent results to previously published findings (e.g., Forrest et al., 1988; Jongman et al., 2000; Nittrouer, 1995).

The fricative productions were spectrally analyzed with 2048-point FFTs. The resulting spectra contained both real and imaginary components. Therefore, only half of

the frequency points were utilized in additional calculations, with the 2048-point FFTs resulting in 1024 real value frequency samples. The additional frequency points with imaginary values were disregarded in subsequent calculations.

Prior to moment calculation the individual FFT spectra were converted to normalized power spectra. This calculation was accomplished by dividing the relative amplitude of each frequency point by the sum amplitude of analysis points. Thus, following Forrest et al. (1988), the normalized power spectra for the FFTs were derived from the following computation:

$$P(k_j) = [P(k_j) / \sum (P(k_1) + \dots + (k_{1024}))]$$

P = relative power
k = real-valued frequency point (j from 1 to 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:

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

P = relative power
k = real-valued frequency point
j = from 1 to 1024

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:

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

P = relative power
 k = real-valued frequency point
 j = from 1 to 1024
 m₁ = spectral mean

The spectral skewness statistic is a reflection of how the acoustic energy is distributed around the mean. This statistic is sometimes referred to as the “spectral tilt” because it conveys the overall slant of acoustic energy. The m₃ was computed as follows:

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

P = relative power
 k = real-valued frequency point
 j = from 1 to 1024
 m₁ = spectral mean

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

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

m₂ = spectral variance
 m₃ = spectral skewness

The fourth spectral moment of kurtosis indicates the peakedness of the spectral distribution. 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:

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

P = relative power
 k = real-valued frequency point
 j = from 1 to 1024
 m₁ = spectral mean

To allow for direct comparisons, the fourth spectral moment was normalized for differences in spectral variance. In the fashion of Forrest et al. (1988), this normalization was conducted by the following calculation:

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

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 programming language by Dr. Shawn Nissen. A corpus of test tokens comprised of known acoustic components was utilized to evaluate the accuracy and reliability of these computer programs. For example, a test token composed of several sinusoidal frequencies (1 kHz, 3 kHz, and 5 kHz) of equal strength was analyzed by the computer programs and found to have the appropriate values for the various acoustic measures.

Statistical Analysis

Repeated-measures analysis of variance (ANOVA) was used to determine significant acoustic variation in the speakers' obstruent productions as a function of magnet presence, placement position, consonant type, and adaptation time. Dependent measures included fricative duration and the first four spectral moments measures. 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. Furthermore, pairwise comparisons for significant within-subject factors were done using

General Linear Model repeated-measures contrasts; comparison significance was determined using the appropriate F -tests.

Results

Descriptive Results of Spectral Analysis

Mean and standard deviation of the dependent variables for the duration, spectral mean, variance, skewness and kurtosis were calculated and are summarized in Tables 1-8. *F*-ratios for main effects and interactions are included in the text.

3-Way Repeated Measures Analysis of Variance

A three-way within-subjects analysis of variance was conducted to evaluate the effect of magnet placement on the spectral and acoustic output for the fricatives /s/ and /ʃ/. The independent variables were magnet condition (with-magnet or without-magnet), magnet placement (10 or 15 mm) and phoneme position in the word (initial, medial, final). The dependent variables were duration, spectral mean, variance, skewness and kurtosis. In addition, data were collected at 5 and 15 minutes after magnet placement and compared to data immediately after magnet placement. These data were used in trend analysis to examine possible adaptation effects.

With and without-magnet conditions. A significant main effect of magnet condition (with or without) was obtained for spectral mean of the fricative /ʃ/, $F(1,9) = 5.68, p < .041, \eta^2 = .387$. The spectral mean of the without-magnet condition was 4789 Hz, whereas the mean for the with-magnet condition was 4671 Hz. However, this change in spectral mean was significant only for the final word position, and will be discussed further as an interaction effect. In addition, there was a main effect $F(1,9) = 6.91, p < .03, \eta^2 = .43$ of magnet condition for the dependent variable of spectral variance. In this case the spectral variance was lower overall ($M = 2.51$ MHz) for the without-magnet condition than for the with-magnet condition ($M = 2.81$ MHz).

Table 1.

Acoustic measures of the phoneme /s/ for without-magnet condition (preceding 10 mm placement. Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	130	31	130	38	119	28
Mean	6093	1641	5469	1597	5914	1180
Variance	2.19	0.51	2.55	0.66	2.44	0.50
Skewness	-1.72	0.71	-1.61	0.87	-1.64	0.66
Kurtosis	1.56	1.91	1.57	2.18	1.41	1.90

Table 2.

Acoustic measures of the phoneme /s/ for 10 mm with-magnet condition. Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	127	25	127	29	122	25
Mean	5679	1546	5801	1306	5915	1469
Variance	2.95	1.15	2.86	1.01	2.59	0.64
Skewness	-1.69	0.70	-1.67	0.71	-1.67	0.75
Kurtosis	1.35	2.13	1.56	2.24	1.65	2.27

Table 3.

Acoustic measures of the phoneme /s/ for without-magnet condition (preceding 15 mm placement). Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	127	16	130	21	160	113
Mean	5534	1387	5813	720	5437	1393
Variance	2.62	0.80	2.62	0.57	2.61	1.03
Skewness	-1.84	0.63	-1.53	0.65	-1.82	0.89
Kurtosis	1.88	2.23	0.81	1.13	2.47	3.17

Table 4.

Acoustic measures of the phoneme /s/ for 15 mm with-magnet condition. Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	127	21	123	22	125	23
Mean	5178	1708	5156	1428	5294	1718
Variance	2.78	0.84	2.98	1.19	2.71	0.85
Skewness	-1.74	0.91	-1.72	1.07	-1.61	0.83
Kurtosis	2.37	4.53	2.75	4.08	1.49	3.19

Table 5.

Acoustic measures of the phoneme /j/ for without-magnet condition (preceding 10 mm placement). Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	134	24	164	108	123	20
Mean	4794	645	4798	528	4997	544
Variance	4.07	1.30	3.89	1.11	4.08	0.93
Skewness	-0.32	0.96	-0.24	0.90	-0.29	0.62
Kurtosis	0.01	0.93	-0.03	0.66	-0.56	0.47

Table 6.

Acoustic measures of the phoneme /ʃ/ for 10mm with-magnet condition. Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	131	24	124	19	128	25
Mean	4776	599	4753	574	4797	519
Variance	3.65	1.37	3.87	1.09	3.81	1.06
Skewness	-0.07	0.77	-0.09	0.77	-0.24	0.79
Kurtosis	0.07	0.61	-0.14	0.66	-0.22	0.57

Table 7.

Acoustic measures of the phoneme /j/ for without-magnet condition (preceding 15 mm placement). Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	134	13	135	17	137	29
Mean	4646	539	4744	650	4753	625
Variance	4.05	1.20	3.70	1.09	4.09	1.13
Skewness	-0.39	0.81	-0.25	0.76	-0.22	0.76
Kurtosis	-0.30	0.75	-0.11	0.76	-0.20	0.89

Table 8.

Acoustic measures of the phoneme /j/ for 15 mm with-magnet condition. Average durations (ms), and the four spectral moments (mean in Hz; variance in MHz; skewness; and kurtosis).

Task	Initial		Medial		Final	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Duration	136	19	130	21	139	23
Mean	4636	508	4527	487	4537	431
Variance	3.78	1.45	3.78	1.14	3.79	1.27
Skewness	-0.25	0.90	-0.12	0.87	-0.16	0.94
Kurtosis	-0.03	1.14	-0.15	1.01	-0.02	1.04

There were no significant effects of magnet condition on skewness or kurtosis of the phoneme /j/, and no significant effects at all for the phoneme /s/ when considering the magnet condition alone.

Magnet position. Magnet position had a significant main effect on spectral mean for both /s/, $F(1,9) = 5.42, p < .045, \eta^2 = .38$, and /j/, $F(1,9) = 10.36, p < .01, \eta^2 = .54$. For /s/ and /j/ respectively, the spectral mean was found to be higher for the 10 mm placement ($M = 5812$ Hz, $M = 4819$ Hz) than for the 15 mm placement ($M = 5402$ Hz, $M = 4641$ Hz).

Word position. There were no significant main effects with word position alone, however, as previously mentioned, there was an interaction effect between word position and magnet condition (see figure 1). For /j/ there was a significant interaction between word position and magnet condition $F(1.888, 16.996) = 4.35, p < .03, \eta^2 = .33$. In other words, for the without-magnet condition the spectral mean was highest in final position ($M = 4871$ Hz), followed by the medial position ($M = 4771$ Hz) with the initial condition having the lowest mean ($M = 4721$ Hz). In the with-magnet condition the outcome was altered with initial position having the highest spectral mean ($M = 4706$ Hz), then the final position ($M = 4667$ Hz), and the medial position with the lowest mean ($M = 4640$ Hz).

Trend Analysis

Polynomial contrasts were utilized to analyze the data collected at 5-minute intervals to investigate possible adaptation effects after the magnet was initially placed on the tongue. The analysis determined that there was not a significant linear effect spanning the without-magnet condition and the two adaptation periods. However, there

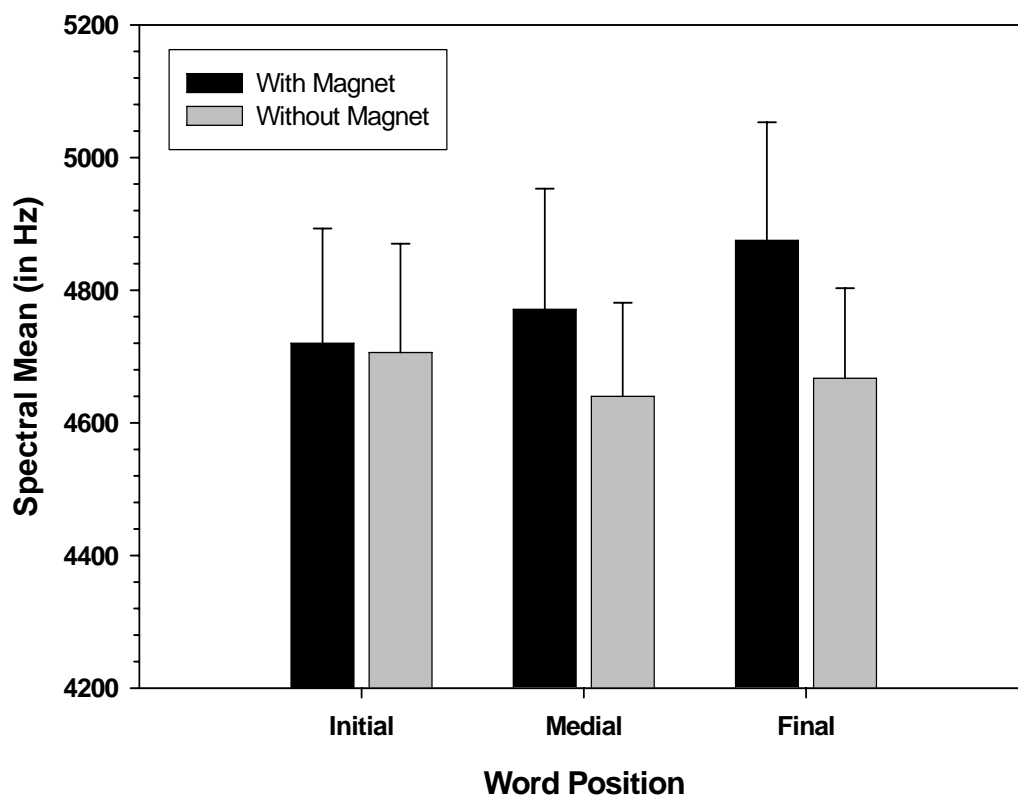


Figure 1. Spectral mean of /f/ as a function of word position and magnet condition.

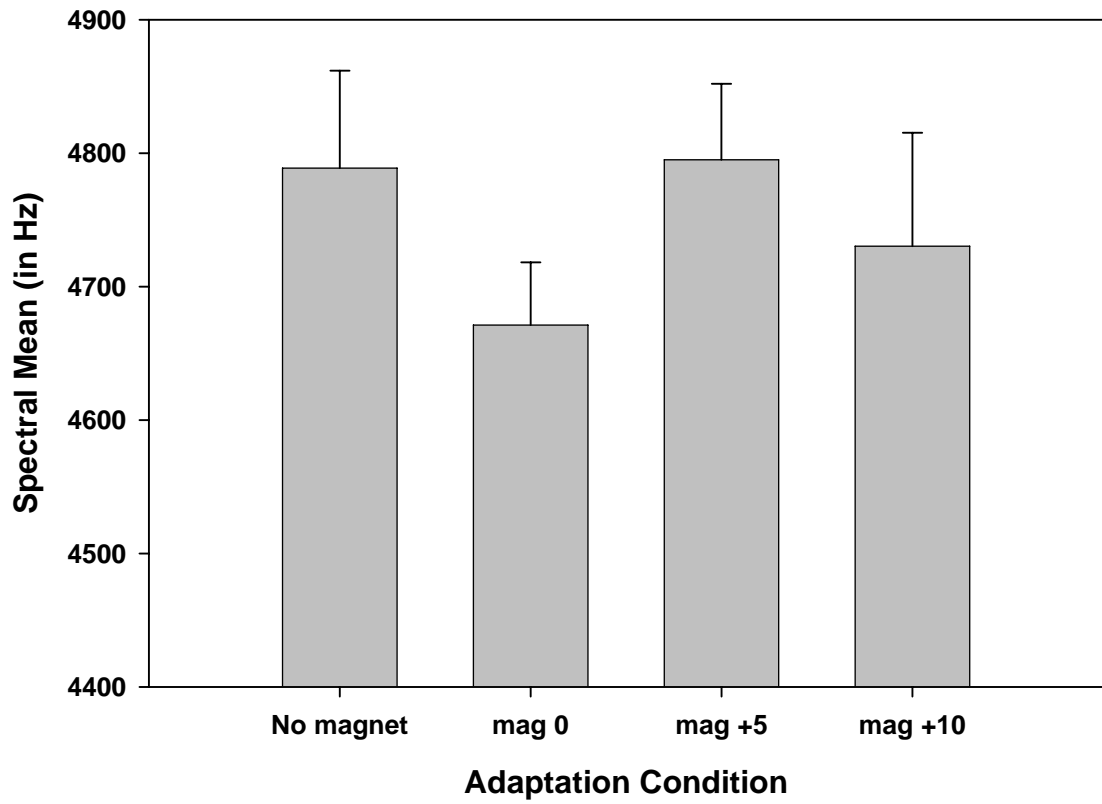


Figure 2. Spectral mean of /j/ as a function of adaptation condition.

was a significant higher order effect $F(1,9) = 8.998, p < .015, \eta^2 = .500$. As shown in figure 2, the spectral mean exhibited a cubilinear trend, whereby the mean dropped immediately after magnet placement, then returned to normal after five minutes of adaptation, then dropped slightly after 10 minutes of adaptation. Also, the spectral variance followed a quadratic trend $F(1,9) = 5.582, p < .042, \eta^2 = .383$, characterized by an increase in variance immediately after magnet placement, the variance then returned to normal after five minutes of adaptation. No other significant trends were found in the polynomial contrasts.

Discussion

Findings from this study indicate that the placement of a traceable device, such as the type of magnet used in a modified JT3 system, does result in the significant disturbance of some of the spectral characteristics of /ʃ/. It was found that the spectral mean and variance of the /ʃ/ productions increased immediately following the placement of the magnet. Previous research suggests several possible reasons for the difference in spectral mean exhibited by the speakers when the magnet was initially placed on the tongue. The increase in spectral mean for /ʃ/ may have been a result of a more forward point of constriction in an attempt to avoid physical interference from the magnet. Another reasonable explanation may be that the presence of the magnet caused a temporary deepening in the midline lingual groove (Fant, 1960), thereby resulting in a slightly higher spectral mean. In addition, the differences in spectral mean may be due to greater subglottal pressure (trans-constriction flows) or higher frequency source energy associated with interruption of laminar flow streams by the magnetic marker (Weismer & Bunton, 1999). Although the spectral mean and variance did decrease when the magnet was in place, it remains unknown if such differences would be great enough to alter a listener's perception.

It is important to note that such differences occurred only when /ʃ/ was being produced in a word final position. Developmental research investigating the acquisition of fricative sound segments may provide some insight into why the /ʃ/ productions in this study were more sensitive to the presence of the magnet. For example, a longitudinal study by Smith and Kenney (1999) found that the final position of /ʃ/ evolved in duration even after the initial and medial positions had stabilized. Although word-position

differences had disappeared by the age of 10, it suggests that the production of fricatives in the final position of words may require much more practice to produce the same phoneme correctly.

The stimulus context also merits scrutiny. In the stimulus sentence “Allison had to miss a sunny vacation at Shellfish Bay,” all positions of /s/ were surrounded by vowels. For /ʃ/, the initial position was immediately preceded by the stop /t/ (which participants tended to produce as unaspirated). In the final position, /ʃ/ was followed by the bilabial stop /b/. Vowels are produced with a constant flow of air through the vocal tract and the tongue in a relatively fixed position throughout its duration. Stops such as /b/ require a build-up of air to realize the characteristic plosive production. It is possible that the anticipation of the following /b/ may have affected the production of /ʃ/ and therefore the spectral realization.

Interestingly, no spectral differences between the magnet conditions were noted for /s/ productions. This decreased vulnerability of /s/ to the presence of the magnet may be attributed to the difference in the formation of the two fricatives. An /s/ fricative is produced by bringing the tongue tip and blade close to the alveolar ridge and grooving the midline of the tongue, whereas an /ʃ/ is produced by elevating the tip and blade of the tongue towards the palate, and fricative noise is made as air passes through the channel between tongue and palate (Shriberg & Kent, 1995). Although the magnet is placed at midline, a placement at 10 or 15 mm from the tongue tip may be posterior enough to avoid interference with the point of constriction used in the formation of /s/. For /ʃ/, however, the tongue approximates the palate posteriorly to the alveolar ridge, so the central conduit for airflow is wider and further back on the tongue. It follows that a

magnet at 10 or 15 mm from the tip of the tongue would be more likely to interfere with the production of this fricative.

For both /s/ and /ʃ/ respectively, the spectral mean was found to be higher for the 10 mm placement than for the 15 mm placement. Higher mean frequencies for the 10 mm placement may be due to a different articulation pattern. Thus, it is possible the tongue had to adopt a different place of constriction because of the magnet placement. The tongue could have had to move forward to accommodate the 10 mm position, or the tongue had to contact further back to accommodate the 15 mm placement (or a combination of the two). The higher frequencies may also be due to a physically shorter front resonating cavity caused by the mass of the magnet itself. In other words, the speakers may be using a similar articulation pattern, but the mass of the magnet is 5 mm closer to the tip of the tongue, creating a shorter anterior resonating space.

One of the most interesting aspects of the study was the adaptation effect. Although the initial placement of the magnet had an effect on the spectral mean and variance of the /ʃ/ productions, speakers were able to adapt to the magnet in a relatively quick amount of time. After 5 minutes of conversation with the magnet in place, no significant differences were noted in any spectral measure for either fricative. Thus, the speakers were able to adapt their articulation so that the spectral realizations of /ʃ/ fricatives with the magnet in place were comparable to productions without the magnet. This conclusion is further supported by the results of the ANOVA and trend analysis. The results of this study are similar to findings reported in previous research (Baum & McFarland, 1997; Kelso & Tuller, 1983; Lindblom et al., 1979). In a similar study, Weismer and Bunton (1999) suggested that it was possible that some tongue positions

and formant frequencies reflected an articulatory adjustment to the presence of the attached devices. Baum & McFarland (1997) speculated that perhaps speakers gradually moved the point of constriction and/or modified airflow turbulence in response to auditory and/or oral-sensory feedback. However, research has also indicated that the adaptation of the articulatory system varies depending on the type of disturbance, the speech sounds being produced, and individual speaker's adaptation strategies (McFarland & Baum, 1995; Munhall, Löfqvist, & Kelso, 1994; Savariaux, Perrier, & Orliaguet, 1995).

This study has some inherent limitations in its scope of research. Although ten participants provide a reasonable degree of validity to the study, it would be ideal to have collected data from a larger number of participants. Also, the magnet was only tested at a midline position on the anterior portion of the tongue. Changing the location of the magnet, perhaps placing it in a more posterior position, or on a specific side of the tongue could conceivably provide more detailed information about the acoustic consequences of attaching a small tracking device to the tongue. Another constraint of the current study is that only two phonemes were studied and both were fricatives. Other phonemes such as stops could potentially have different effects with the magnet. However, the use of /s/ and /ʃ/ can be considered a rigorous test, as fricatives are among the speech sounds most susceptible to acoustic disturbance (Weismer & Bunton, 1999).

Despite these limitations, this study is still a valuable contribution to speech research. Many of the methods used to track tongue movements involve attaching a device to the articulators. As Weismer and Bunton (1999) point out, there is little research regarding the effects these devices may have on speech production behavior.

The overall findings of this study are consistent with the findings of previous researchers (Weismer & Bunton, 1999) who report that spectral moments analysis failed to reveal a pervasive and persistent effect of attached pellets on articulation of fricatives phonemes. Similar to the findings of previous researchers, this study supports the assertion that attaching a small tracking device to the tongue does not have a pervasive and persistent effect on the fricative production of typical adult speakers and the limited acoustic disturbance that occurs is usually adapted to with a relatively short amount of conversational speech.

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Appendix

Consent to be a Research Subject

Introduction

This research study is being conducted by Andrea Weaver, a graduate student in speech-language pathology at Brigham Young University. Her work will be supervised by Dr. Shawn Nissen, who is a member of the faculty. The goal of the research is to examine the effects of magnet placement on acoustic and spectral output of speech. You were selected to participate because you met the necessary language requirements (native English speaker with no known history of a speech, language or hearing problem).

Procedures

Participation in this study will involve two visits of approximately 25 minutes to a Speech Research Laboratory in the John Taylor Building on the campus of Brigham Young University. You will be seated in a chair in a sound booth and will have a small magnet attached to your tongue with dental adhesive. You will perform speaking tasks while we make recordings of your speech. Specifically you will be asked to repeat a sentence and engage in conversation with the individual administering the experiment.

Risks/Discomforts

There are minimal risks for participation in this study. It is possible that you might experience minor skin irritation from the glue that attaches the magnet, although this has never occurred with the past use of this equipment. It is also possible that you may swallow the magnet that will be attached to your tongue. If this were to happen, the non-toxic, smooth, nickel-plated magnet would simply pass through the digestive system.

Benefits

There are no direct benefits to subjects. However, it is hoped that through your participation researchers will learn more about the acoustic effects that certain articulatory tracking devices may have on typical speech production.

Confidentiality

All information provided will remain confidential and will only be reported as group data with no identifying information. All data, including digital recordings of your speech will be kept in a locked storage cabinet and only those directly involved with the research will have access to them.

Compensation

No monetary compensation is offered. However, a summary of the findings of the study will be provided to you upon request.

Participation

Participation in this research study is voluntary. You have the right to withdraw at anytime 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 Dr. Shawn Nissen at 801-422-5056, Shawn_Nissen@byu.edu.

Questions about your Rights as Research Participants

If you have questions you do not feel comfortable asking the researcher, 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 and desire of my own free will and volition to participate in this study.

Signature: _____

Date: _____