2009-03-02

Associations Between Linguapalatal Contact Patterns and Spectral Moments for /s/

Leslie Leatham Bennett
Brigham Young University - Provo

BYU ScholarsArchive Citation

Bennett, Leslie Leatham, "Associations Between Linguapalatal Contact Patterns and Spectral Moments for /s/" (2009). *Theses and Dissertations*. 1668.
https://scholarsarchive.byu.edu/etd/1668

ASSOCIATIONS BETWEEN LINGUAPALATAL CONTACT PATTERNS AND SPECTRAL MOMENTS FOR /S/

by

Leslie L. Bennett

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

April 2009

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Leslie L. Bennett

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date Christopher Dromey, Chair

Date Shawn L. Nissen, Member

Date Ron W. Channell, Member

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate’s graduate committee, I have read the thesis of Leslie L. Bennett 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.

Date

Christopher Dromey
Chair, Graduate Committee

Accepted for the Department

Date

Ron W. Channell
Graduate Coordinator

Accepted for the College

Date

K. Richard Young
Dean, David O. McKay School of Education

ASSOCIATIONS BETWEEN LINGUAPALATAL CONTACT PATTERNS AND SPECTRAL MOMENTS FOR /S/

Leslie L. Bennett
Department of Communication Disorders
Master of Science

Abstract

Both acoustic and palatographic measures have proven to be useful in speech science research. However, it is not known how closely or consistently these two measures are associated with each other. Therefore, this study investigated the association between changes in tongue-to-palate contact patterns and simultaneous changes in acoustic spectral moments for the fricative /s/. Twenty adults were fitted with pseudopalates and repeated VCV nonsense syllables consisting of an initial schwa followed by the target consonant /s/ and ending with one of three corner vowels (/i, ɑ, u/). EPG (electropalatography) data were quantified using three custom numerical indices (s-narrow, s-wide, and asymmetry) derived from specified zones on the pseudopalate which loosely reflected dimensional differences in the fricative groove. These indices produced general details about changes in tongue contact over time, but index values were not unique to specific contact patterns. The EPG numerical index values were then compared

with differences in spectral moments (spectral mean and variance) from the time-aligned acoustic signal. On the whole, all combinations of spectral mean and variance and EPG indices resulted in some weak but significant correlations across all vowel contexts and participant groupings. The majority of these correlations were negative, meaning that as EPG index values increased, spectral mean and variance decreased. Some of the strongest of these correlations were present between s-narrow and spectral mean and variance. Therefore, in order to give a clearer picture of the link between lingual physiology and spectral moments, these variables were correlated for each individual speaker. Stronger significant correlations between s-narrow and both spectral mean and variance were identified in some participants. The majority of these correlations were also negative, suggesting that as the s-narrow index increased, the spectral mean and the variance decreased. A few participants' results that showed interesting lingua-palatal contact patterns are discussed in more detail. Generalization based on specific correlations from this study must be undertaken with considerable caution due to desynchronization of EPG data and the acoustic signal found in several tokens.

ACKNOWLEDGMENTS

Several individuals deserve sincere thanks and acknowledgement in the completion of this thesis. First I must acknowledge Dr. Dromey, whose support, vision and creativity made the successful completion of this project possible. Dr. Nissen and Dr. Channell, members of my thesis committee, whose help and input were also invaluable. I also want to express gratitude to Matthew, the best late-night lab partner, for his unfailing support, encouragement, perspective and humor. My parents for instilling in me a love of science and learning and also for their continued interest in my well-being and this project. Jessie for her companionship, understanding and example. And of course to my Father in Heaven who so graciously answered countless little and not-so-little prayers along the way.

TABLE OF CONTENTS

Page

Table of Contents ... vii

List of Tables ... x

List of Figures ... xi

Introduction ... 1

Acoustic Analyses ... 1

Contributions of Spectral Measure Analyses to Speech Science ... 5

Palatometry ... 8

History of Palatometry ... 8

EPG Data Management Systems ... 10

Contributions of EPG to Clinical Practice and Speech Science ... 12

Motor Equivalence and Acoustic-to-Articulatory Mismatch ... 15

Purpose of Study ... 18

Method ... 20

Participants and Materials ... 20

Stimuli and Procedures ... 20

Measurement ... 21

Spectral Moments Analysis ... 22

EPG Numerical Indices ... 24

Alignment of Spectral Moment Analysis and EPG Indices ... 31

Statistical Analysis ... 33

Results ... 35

40 Ms Spectral Moments Results ... 35

Group Results 35

Individual Results 38

20 Ms Spectral Moments Results 38

Group results 38

Individual results 43

Illustrative Cases 45

Case One 45

Case Two. 49

Case Three 49

Case Four. 55

Case Five 55

Discussion 60

40 and 20 ms Results 60

Large Group Spectral Moments 60

Individual Spectral Moments 61

Illustrative Cases 62

Case One 62

Case Two 62

Case Three. 63

Case Four.. 63

Case Five 64

Limitations 64

Conclusions and Suggestions for Future Research 66

References..67

Appendix..71

LIST OF TABLES

Table Page

1. Groups Significant Pearson r Correlations for 40 ms Spectral Moments and EPG Indices. 36
2. Individual Participants' Significant Pearson r Correlations for 40 ms Spectral Measures and the s-narrow EPG Index 39
3. Groups Significant Pearson r Correlations for 20 ms Spectral Moments and EPG Indices 40
4. 40 ms and 20 ms Large Group Results Comparison........ 44
5. Individual Participants' Significant Pearson r Correlations for 20 ms Spectral Measures and the s-narrow EPG Index 46
6. 40 ms and 20 ms Individual Participants' Results Comparison. Spectral Moments are Uncapped 47

LIST OF FIGURES

Figure Page

1. Representation of the spectral moments sampling windows.. 23
2. S-narrow EPG index 25
3. Palatal contact patterns and their corresponding s-narrow EPG index values...... 27
4. S-wide EPG index.. 29
5. Contact patterns for the s-wide EPG index... 30
6. Contact patterns for the Asymmetry EPG index... 32
7. Illustrative case number one 48
8. Tongue-to-palate contact patterns for case one 50
9. Illustrative case number two 51
10. Tongue-to-palate contact patterns for case two 52
11. Illustrative case number three 53
12. Tongue-to-palate contact patterns for case three 54
13. Illustrative case number four 56
14. Tongue-to-palate contact patterns for case four.. 57
15. Illustrative case number five... 58
16. Tongue-to-palate contact patterns for case five.. 59

Introduction

Acoustic analysis and palatometry are valuable tools that enable speech scientists to obtain a detailed understanding of the production of human speech sounds. Acoustic analyses generally, and spectral measures more specifically, can reveal subtle details and distinguishing characteristics of individual speech sounds. Palatometric measures can directly reveal articulatory tongue-to-palate contact patterns. However, it is not known how closely or consistently these two measures are associated with each other. Few studies have examined in detail the link between palatometric and acoustic data. Therefore, the purpose of this study is to investigate how strongly acoustic spectra and tongue-to-palate contact patterns are associated with each other.

Acoustic Analyses

A primary goal of many speech scientists is to understand human speech production in the greatest amount of detail possible. One approach has been to examine it through the end result—the acoustic signal. In the 1920s researchers found a method to record acoustic signals using an oscillograph which relied on string galvanometers to record a graphic representation of the sound wave known as an oscillogram. Vowels were the easiest speech sounds to record on an oscillogram because of their periodic nature (Kent & Read, 2002). Over time, more sophisticated methods of recording and representing sound pressure waves were developed. For a few decades, oscilloscopes were used to display a waveform by using a narrow beam of electrons directed at a screen. This beam was electronically deflected to reveal the movements of the sound waves. This waveform could be temporarily captured in a storage oscilloscope or photographed to produce a permanent record. Additionally, speech signals were often sent to a plotter which used pens or light to transfer the waveform to a roll of treated paper (Borden & Harris, 1984). Analog tape recording was also a convenient and inexpensive way to store data, but this technology is not typically used today.

With the development of digital technology and the ubiquity of the personal computer, acoustic signals can be recorded, stored, visually displayed, and analyzed digitally. A recorded waveform can be used to reproduce a sound, detect temporal variations in a signal, and identify distortions such as peak clipping or background noise. With accurate digital recordings, speech scientists are able to examine minute details of the recorded waveform such as sound duration, amplitude, periodicity, and fundamental frequency. Editing the waveform is also possible (Kent & Read, 2002).

Although waveform representations of speech are useful, they have some limitations. For example, in the past oscillograms were most commonly used to record the waveforms of vowels. However, it is difficult to distinguish different vowel sounds by examining the waveform alone. This is because the waveform cannot give specific representations of the different frequency components of vowels (Kent & Read, 2002). In the mid 19th century Hermann Von Helmholtz developed Helmholtz resonators (hollow globes of glass tuned to different frequencies) that he sealed to his ear with wax and then used to listen to complex sounds. The resonators only resonated at their own natural frequencies and thus Helmholtz was able to derive and document fundamental frequencies and harmonic characteristics of human speech sounds (Borden & Harris, 1984). The Henrici Analyzer was also developed in order to provide a spectral analysis of speech signals. To do this, an operator would hand trace a portion of a waveform with the Henrici Analyzer. Then the operator would calculate the amplitudes, phase relationships and also the sound pressure in decibels of specific frequency components of a complex speech signal. However, this method was inaccurate because it was based on the assumption that speech is perfectly periodic. Although speech is made up of patterns of sound waves, it is only quasi-periodic. Still, this method proved that there were frequency concentration differences between vowels, and it paved the way for modern spectral analysis of speech (Kent & Read, 2002).

Filtering was also used to examine the harmonic components of complex speech signals. By using a filter bank, a speech signal could be passed through a number of separate band-pass filters at specific frequencies, revealing the energy present in each frequency band. This approach contributed to an improvement in the understanding of acoustic signals because it could also analyze speech sounds containing noise (Kent & Read, 2002).

In the 1940s the spectrograph was developed, which facilitated faster spectral analysis of speech and the ability to study increased volumes of data. The spectrograph used variable band-pass filters to create a spectrogram that represented the frequency concentrations in speech recordings over time. Originally, the spectrogram was produced on treated paper with a heated marking stylus. With the development and refinement of computers and software for speech analysis, spectrograms can now be created and displayed digitally (Kent & Read, 2002). Spectral representations of speech are often referred to as frequency domain displays since frequency, not time, is displayed on the abscissa. These approaches allow the extraction of details from speech signals that would not be available from the waveform display. For example, spectral analyses allow researchers to observe differing amplitudes of a sound’s component frequencies and movement of formants (resonances of the vocal tract) over time. Moreover, statistical analysis techniques can be applied to spectra in order to reveal important characteristics of specific speech sounds (O'Shaughnessy, 1987).

Several analysis techniques have been developed that use spectral representations of speech sounds. One analysis tool, called the Fast Fourier Transform (FFT), changes a series of data points in a time-domain waveform into a frequency domain spectrum that displays the amplitudes of the different frequency components in the signal. This has helped clarify the defining characteristics of speech sounds by providing a representation of the differing amplitudes of a sound's component frequencies. For example, FFT shows how the amplitudes of different harmonic frequencies change in different vowels. Thus, FFT is a useful tool for showing aspects of the source of a sound. Linear predictive coding (LPC) is another analysis technique that also changes a segment of the time-domain waveform into a frequency-domain display. However, it is different from the Fast Fourier Transform in that it displays a smoothed spectral envelope showing the formant frequencies and their amplitudes. Therefore, LPC is a useful tool that reveals much about the vocal tract transfer function of speech sounds (Kent & Read, 2002).

Many different spectral measures have been derived from FFTs and LPCs which are useful in analyzing acoustic spectra. However, for the purposes of this study, four specific spectral moments will be considered. Nissen (2003) describes spectral moments as statistical, "…spectral 'snap-shots…'" (p. 13) that are derived from an FFT. These spectral moments target different attributes of the acoustic spectrum. The first spectral moment, spectral mean, gives the average of the energy distribution of the FFT spectrum. Spectral variance is the second moment and describes the variance of frequencies which are included in the spectrum, or the degree to which they spread around the mean.

Spectral skewness, the third spectral moment (also referred to as spectral tilt), expresses the skewness of the spectrum's frequency distribution either positively or negatively in relation to the mean. The fourth spectral moment, spectral kurtosis, is an index of the peakedness of the spectrum. Therefore, a lower kurtosis value would describe a spectrum that does not contain distinct spectral peaks (Nissen, 2003).

Contributions of Spectral Measure Analyses to Speech Science

Acoustic analysis has played a major role in speech science in furthering the understanding of several aspects of speech production. Acoustic analyses have helped speech scientists better understand acoustic details such as age-related differences in speech production (Fox & Nissen, 2005; Nissen & Fox, 2005), children's differing rates of acquisition of speech production (Nittrouer, 1995), and spectral differences in phonologically disordered speech (Forrest, Weismer, Elbert, & Dinnsen, 1994; Forrest, Weismer, Hodge, & Dinnsen, 1990). Additionally, spectral measures have been used to study how rate of speech affects obstruent production and how spectral measures can identify the place of articulation of speech sounds from acoustic signals.

For example, Fox and Nissen (2005) measured the vowel duration, amplitude, and spectral measures for the fricatives /f, ɵ, s, ʃ/ in the speech of adults and pre- and post-pubescent children from the ages of six to fourteen. The participants were asked to read words that contained the target phonemes in CV combinations. Acoustic measures included spectral moments, focusing on the first, third, and fourth moments. Other analyses also included fricative duration, vowel duration, spectral peak, spectral slope, root-mean squared amplitude, and normalized amplitude. Discriminant analysis of these measures was used to determine which variables (speaker age, sex, place of articulation) were the most easily discernable by these acoustic measures. The authors reported that changes in the spectral peak and first, third, and fourth spectral moments were successful in indentifying specific places of articulation. Spectral slope was able to distinguish /s/ from /f/ and /ɵ/ for all age groups. The authors also reported that /s/ could be discriminated from /f/ and /ɵ/ through spectral peak values in men but not women.

In another study, Kardach et al. (2002) used spectral measures to compare obstruent characteristics of typical speech versus speech produced during simultaneous communication (speech combined with manual methods of communication such as signing and fingerspelling). Speaking occurs at a slower rate when using simultaneous communication because of the need for speech to be simultaneous with the manual communication methods, which are by nature slower. In order to compare the spectral characteristics of obstruents during simultaneous communication, the authors collected speech samples from 12 faculty members from the National Technical Institute for the Deaf whose simultaneous communication skills were advanced. The speakers were recorded saying CV combinations of four consonants and three corner vowels in a carrier phrase five times each with speech alone and then with simultaneous communication. The first, third, and fourth spectral moments were computed for both conditions and then compared with each other. The authors reported that there were no significant differences in the obstruents’ spectral moment measures despite the slowed rate of speech during simultaneous communication. Therefore, the authors claimed that the slowed rate did not alter the obstruents, and listeners should have no more difficulty identifying these sounds than when they are presented as speech alone without simultaneous communication.

In 2000 Jongman, Wayland, and Wong examined English fricatives using several acoustic measures. Ten male and ten female adult speakers of American English were asked to produce the eight English fricatives /f, v, ɵ, ð, s, z, ʃ, ʒ/ in CVC combinations in the carrier phrase, “Say ____ again.” The target fricative was in the initial position and the final consonant was /p/. The participants were asked to repeat each word three times. The data were then analyzed by using acoustic analyses such as spectral peak location, spectral moments, locus equations (equations that represent the relation of F2 at different points in time), normalized amplitude (fricative amplitude minus the vowel amplitude; used to eliminate intensity differences between speakers), relative amplitude (the difference between fricative amplitude and the vowel amplitude of F3 or F5, depending on the target sound), and noise duration. Then discriminant analysis was used to determine whether or not the fricatives could be distinguished (as to place of articulation) by the use of these acoustic parameters. The researchers found that the spectral and amplitude data were the most accurate in predicting the fricatives’ place of articulation. Spectral peak location and spectral moments were successful in distinguishing all four places of articulation. The authors also reported that both normalized amplitudes and relative amplitudes were able to denote fricative placement. However, the authors reported that F2 transition properties and noise duration measures did not distinguish between the four places of articulation. They concluded that some acoustic analyses could distinguish all four places of fricative articulation, “…despite variation in speaker, vowel context, and voicing” (p. 1262).

Spectral analyses have provided speech scientists with valuable insights into human speech production. They have shed important light on issues such as speech acquisition, disordered production, treatment efficacy, and dialect differences. This type of information would not be available from an examination of the raw waveform alone. Of spectrographic representations Farmer (1997) asserted that they, "…[have] been the single most useful device for the quantitative analysis of speech" (in Ball & Code, 1997, p. 22).

Palatometry

Although acoustic measures can reveal a great deal about human speech, they cannot give a detailed representation of the actual movement and physiology involved. For example, some speakers may use more than one physiologic means to produce different versions of the same sound which may not be acoustically or perceptually distinguishable from each other, a phenomenon known as motor equivalence. These subtle differences in speech production often involve the tongue and are not typically revealed via acoustic analyses. It is difficult to visually observe these lingual changes in speech production because the tongue is a flexible organ that is constantly changing shape during speech and is usually hidden behind the teeth and lips. Therefore, due to the inherent ambiguity involved when using acoustic analyses to identify slight changes in speech production and the difficulties in observing the tongue due to its anatomical characteristics and placement, several researchers have developed ways of graphically representing tongue contact against the palate. These graphical representations are called palatography and they can allow inferences about lingual shape and movement during speech.

History of palatometry. In 1872 English dentist J. Oakley Coles coated his hard and soft palate with a dry mixture of flour and gum which was wiped clean where the tongue touched the palate when he articulated specific sounds (Fletcher, 1992). He then painted the tongue patterns left on his palate onto a model made from his own dental impression. In 1879 Grützner coated speakers' tongues with Chinese red rouge and then recorded the red patterns left on the palate from articulated sounds. Kingsley, in 1877, used a pressure molded rubber plate coated with chalk for speakers to articulate against. The plate was removed after articulation and the pattern for articulation recorded. Although these researchers had developed working methods of documenting tongue-to-palate contact patterns, serious obstacles to the understanding of lingual physiology remained. The main limitation was that these representations only displayed maximum contact. No details concerning movement over time or force could be observed or recorded (Fletcher, 1992). The use of electricity in palatography would soon help researchers begin to overcome these limitations.

As early as the 1930s researchers began to use electricity in palatography, and by 1964 continuous palatography was developed by Kydd and Belt (1964). This technique relied on an artificial palate in which 12 electrodes were embedded. These electrodes were attached to insulated copper wires and then to an amplifier. The amplifier was then connected to a series of lights positioned in such a way as to represent the electrodes' placement on the pseudopalate. Motion picture recordings were made to provide a permanent record of the speakers' tongue-palate contact patterns.

By 1975 Fletcher, McCutcheon, and Wolf reported the use of dynamic palatometry using a computer-based system for documenting continuous palatometry. The palatometer system they described used a pseudopalate 2 mm thick which contained 48 electrodes. The signals from the electrodes were carried through wires to an amplifier, then on to a digitizer, read into computer memory, recorded on magnetic tape, and then viewed on a light emitting diode (LED) display. This system allowed the lingual-palatal contact data to be displayed temporally alongside acoustic data or to be displayed as an average of several syllable repetitions.

Since 1975 electropalatography has made several advances. Pseudopalates have become thinner and more comfortable and more electrodes are used in order to obtain greater detail. Furthermore, the development of pressure-sensing electropalatography may be a possible advancement in future palatometers (Murdoch, Goozée, Veidt, Scott, & Meyers, 2004; Searle, 2003). Modern electropalatography typically requires a personal computer and software specific to the type of palatometer in use. It is important to note that there is a distinction between the terms palatography and palatometry. Palatography shows patterns of contact whereas palatometry measures the details of articulation quantitatively. Some researchers feel strongly about making this distinction while others use the terms interchangeably.

One current palatometric system is the LogoMetrix palatometer. The LogoMetrix system uses a flexible printed circuit which contains 116 electrodes in a 3.5 mm grid. It is glued to a thin, flexible baseplate that is custom made from a stone model of the participant’s upper teeth and palate. When the tongue contacts the electrodes on the pseudopalate, small black dots on the computer monitor temporarily change to larger blue circles to indicate tongue contact. Palatometric data are stored along with the acoustic signal for playback or further analysis.

EPG data management systems. In order to more effectively manage the high volume of data when using palatometers, several numerical indices have been developed.

Hardcastle, Gibbon, and Nicolaidis (1991) described two contact distribution indices, the Center of Gravity (COG) Index and the Anteriority Index, and four other indices: the Asymmetry Index, the Coarticulation Index, the Trough Index, and the Variability Index. The COG Index shows the main concentration of electrodes that have been activated across the entire palate with a single numerical value. The COG can also be displayed on a graph with the vertical axis representing anteriority of tongue contact while the number of contacts is shown by the length of a vertical line superimposed on the COG value. The values increase toward more anterior rows of electrodes.

Similarly, the Anteriority Index also represents the concentration of electrodes activated but weights the front and back electrodes on the pseudopalate more than electrodes placed in the center. The Anteriority Index divides the pseudopalate into zones from front to back and calculates the number of electrodes in each zone that have been contacted. This is because significant differences in speech sounds occur in the most anterior or posterior parts of the palate (Hardcastle et al., 1991).

Another index, the Asymmetry Index, totals the number of electrodes that have been activated on the right side or left side of the palate as a function of the total number of electrodes. Asymmetries more localized to the right side are shown as positive values and asymmetries more localized to the left side are shown as negative values. This is a useful index because both normal and pathological speech patterns involve asymmetrical productions. Therefore, the Asymmetry Index allows researchers to determine what amount of asymmetry is tolerable and if there are any asymmetrical tendencies in classes of sounds, dialects, or languages.

The Coarticulation Index (CI) reveals the coarticulatory effects of vowels on consonant production. During the first frame of complete anterior closure following a vowel, the total number of electrodes activated in each of eight rows is counted and is represented as the, "…percentage of maximum possible contactable electrodes in that row" (p. 260). The average between the values for the eight rows is the coarticulation index. This index is useful in portraying effects of vowel environment, anticipatory effects on consonants followed by vowels, and patterns specific to languages.

The Trough Index (TI) reflects lingual "relaxation" during intervocalic consonants, specifically when the consonant gesture is independent of the vowel (e.g. bilabials such as /p/ and /b/). The TI is calculated by noting the change in the row with the highest electrode activation during the vowel and then again during the consonant. The TI has shown significant differences between voiced and voiceless bilabial stops (i.e. a higher TI for voiceless bilabial stops).

The Variability Index (VI) expresses variability either contextually or within an utterance. Contact patterns are represented by a 63 dimensional vector (based on the Rion EPG system). The frame with maximum electrode activation is selected and the average vector for all the utterances is calculated along with the distance between the average vector and the vector of each utterance. This difference is the standard deviation and thus higher values indicate more variability (Hardcastle et al., 1991).

Contributions of EPG to clinical practice and speech science. Palatometry has been used to evaluate several aspects of disordered articulation. For example, Hardcastle, Gibbon, and Scobbie (1995) used EPG to determine the place of articulation of /t/, /ʃ/, and /tʃ/ in ten children with normal production of /t/ but an inaccurate production of /ʃ/.

Each child read aloud eighteen words containing the target sounds. For analysis, specific segments were identified from the acoustic signal and then the time-aligned EPG data were examined. The acoustic focus for /t/ was the midpoint between the closure and release of the stop. For /ʃ/, the acoustic segmentation was made in the midpoint of the frication. The acoustic targets for /tʃ/ included 2 frames: the midpoint between the closure and release of the stop, and the midpoint between the release of the stop and the end of the fricative. Then the frequency of EPG electrode activation at these time points was calculated. The selected frames for each sound were averaged and made into four composite EPG frames. The authors found that when /ʃ/ was advanced or retracted, /tʃ/ was advanced or retracted as well. They also noted that in some cases the closure phase of the affricate had a coronal placement when /ʃ/ was produced in a dorsal placement. The authors suggested that the children in this study must be aware at some level of the relationship of this affricate to the alveolar stop. The authors speculated that perhaps once a child has mastered correct articulation of /t/ and /ʃ/ the affricate may not require therapeutic intervention.

McAuliffe, Ward, and Murdoch (2006) used EPG to examine tongue-palate contact patterns in a group of nine elderly speakers with Parkinson's disease in order to determine whether their imprecise articulation of consonants was due to "…a reduction in the amplitude of lingual movements or articulatory undershoot" (p. 1). The authors found that these speakers did not exhibit a reduction in tongue-palate contact in association with their perceived errors. This finding does not support the theory that imprecise consonant production in Parkinson's disease is due to reduced lingual movement or articulatory undershoot. The authors suggested that these findings could be due to the fact that the participants only exhibited a mild dysarthria or that the participants' articulatory imprecision could be caused by a deficit in the pressure of tongue-palate contact or difficulties in articulatory timing.

EPG has also been used to study differences in the speech of those who stutter. Forster and Hardcastle (1998) used EPG to determine whether or not participants who stutter had different tongue-palate contact patterns and greater intra-speaker variability than control speakers. They also sought to document what changes the participants' tongues made during disfluent speech. Qualitative comparisons of fluent speech were analyzed to determine characteristics of the participants' repetitions and prolongations. The authors discovered that during fluent speech the participants who stuttered displayed, "inappropriate muscular activity of the tongue" (p. 363). Stutterers' alveolar and velar plosives displayed an increase in palatal contact and fricatives were produced with less contact. The authors suggested that these two phenomena could be caused by increased muscular tension. It is also possible that the lack of contact with which the fricatives were produced could be evidence of a fluency strategy used by the stuttering participants to avoid hard contacts. Additionally, during disfluent speech EPG data revealed that the initial phoneme was similar to the target but each attempt made by the stutterer became more aberrant compared with the target phoneme.

Electropalatography has also been helpful in observing abnormal speech patterns in individuals with cleft palate. Gibbon (2004) reported eight abnormal patterns of tongue-palate contact in children and adults with cleft palate using EPG data from a compilation of several projects by a multidisciplinary team at Queen Margaret University

College, Edinburgh and four cleft palate centers in Scotland. Gibbon reported that more research is needed in studying speakers who have achieved “normal” speech. She also suggested that further research should investigate contact patterns for consonant clusters and examine which abnormal contact patterns will respond best to therapy.

Motor equivalence and acoustic-to-articulatory mismatch. The use of EPG in speech science research has also shed light on motor equivalence in that some studies have documented inter- and intra-speaker variability in tongue-palate contact patterns that are not always discernable in accompanying acoustic analyses.

McAuliffe, Ward, and Murdoch (2001) fitted ten normally speaking adults with palatometer pseudopalates and recorded their tongue-to-palate contacts along with the acoustic signal. Targeted consonants included /t/, /l/, /s/, and /k/ in CV combinations using the /i/ vowel. For the consonant /l/ a CVC word (“leap”) was used. Using a relative variability index developed by Farnetani and Provaglio (1991), the authors found that /l/ demonstrated higher intra-speaker variability than both /t/ and /s/. The authors speculated that this could be because of the small amount of dorsal and posterior tongue support required for /l/ production. This stands in contrast to the lateral stabilization required for the production of the phoneme /t/ which, as expected, was significantly less variable than /l/. The authors also noted that the difference in variability between /l/ and /k/ was not significant and suggested that if the pseudopalate extended farther into the oral cavity, “…a greater picture of stability would have resulted” (p. 176). The authors also reported that intra-speaker variability for /s/ was significantly lower than for /l/ and that this could be due to full lateral contact that stabilizes the tongue for consistent production of the consonant.

In a study by Sanders (2007), tongue-to-palate contact patterns of ten male and ten female standard American English speaking adults were recorded while they spoke nonsense VCV words containing 15 lingual consonants and the vowels /i, ɑ, u/. The initial vowel was a schwa with one of the three corner vowels following the target consonant. Sanders used these palatometric recordings to create a variability index to examine inter- and intra-speaker variability. Place of articulation, manner of production, the phonemes /l/, /r/, and /s/, and coarticulation effects were all examined for their impact on variability. Concerning place of articulation, alveolar consonants were significantly more variable than the corresponding velar sounds in the /i/ vowel context. In the /ɑ/ vowel context, manner of production exhibited differing degrees of variability for the consonants /d/, /z/, /n/, and /l/. No significant difference in variability relating to consonant voicing was found. Production of /r/, /l/, and /s/ in the /ɑ/ vowel context were found to be significantly different in their degree of variability, and consonants coarticulated with /u/ were significantly more variable than consonants coarticulated with /ɑ/. Additionally, Sanders found that speakers who were more variable in repeated productions in one vowel context were likely to demonstrate high variability in another vowel context. She also qualitatively described aspects of consonant production including observations of increased tongue-to-palate contact for consonants in the /i/ vowel context (likely due to the high placement of the /i/ vowel) and that in the /ɑ/ and /u/ vowel contexts incomplete closure was noted for velar phonemes.

Tabain (2001) compared acoustic and EPG data from the fricatives /ɵ, s, ʃ, ð, z, ʒ/ spoken by four Australian adult females by using the spectral and electropalatographic center of gravity measures in order to assess coarticulation of fricatives. The participants produced target CV syllables in the carrier phrase, “Doctor _ _ba.” The speakers were asked to read the list of target syllables twice to become accustomed to the EPG pseudopalate after which a third reading was kept for analysis. The EPG data showed a large degree of inter-speaker variability especially for /ð/. Tabain reported that one speaker had almost no contact for this sound and speculated that because this participant had a very narrow palate, she might have been producing the phoneme by making contact between the tongue and the teeth. Additionally, two of the speakers displayed a more forward articulation of /z/ with a narrow central channel while the other two speakers had more retracted productions with a wider central channel. The spectral COG measures were lowest for /ʃ, ʒ/, highest for /s, z/, and medium values were noted for /ɵ, ð/. Tabain concluded that nonsibilants showed more variability than sibilants and that consonants such as /ɵ, s/ demonstrated greater coarticulation than consonants with more tongue body raising. Additionally, despite the variability in production, Tabain also concluded that EPG COG and spectral COG were correlated.

In another study, Hoole, Nguyen-Trong, and Hardcastle (1993) used EPG and acoustic data to compare coarticulation of the fricatives /s/ and /ʃ/ in two English speakers, two German speakers, and two French speakers. The participants produced the target fricatives in nonsense words using the vowels /i, u, ɑ/ in VCV combinations. The nonsense words were spoken in random order five times. EPG and acoustic recordings were made. The center frames of the fricatives were acoustically analyzed by using a Fourier Transform. The spectral center of gravity and spectral dispersion were also derived. The EPG pattern that corresponded to the center frame of each fricative in the acoustic signal was converted to a vector of eight values by adding the number of contacts made in each row. The authors found that all six speakers showed more contact in the posterior four rows for /ʃ/ than /s/. It is interesting to note that one of the German speakers exhibited a fairly retracted production of /ʃ/ comparative to the other speakers, but this was not obvious in the acoustic data. The French speakers did not show as much of an articulatory difference between /ʃ/ and /s/ as did the English and German speakers because of a large amount of contact for the /s/. This was also unclear in the acoustic data. In general, the authors reported that for three of the six speakers (one speaker of each language), "…the overall *pattern* of the acoustics follow[ed] that of the EPG results closely…" (p.250). However, the authors also reported that for the other three participants, patterns of anticipatory or carryover coarticulation seen in the EPG data are somewhat unclear and sometimes absent in the acoustic data. The authors concluded that mismatches between acoustic and articulatory data were not rare.

Purpose of Study

Both acoustic and palatographic measures have proven to be useful in speech science research. However, it is not known how closely or consistently these two measures are associated with each other. Remember that Hoole et al. (1993) reported that there were some instances of motor equivalence (one speaker's retracted production of /ʃ/ and another speaker's predominance of carryover) that were not acoustically identified, thus resulting in mismatches between acoustic and articulatory data. In contrast, Tabain (2001) reported that the COG measures for both acoustic spectra and EPG tongue patterns were correlated. Therefore, considering documented intra- and inter-speaker variability and inconsistent acoustic manifestations of such variability, the purpose of this study was to investigate how strongly acoustic spectra and tongue-to-palate contact patterns are associated with each other.

This study investigated the association between changes in tongue-to-palate contact patterns in specified zones on the pseudopalate and simultaneous changes in acoustic spectral moments for the fricative /s/. Changes within these zones were quantified with palatometric indices which loosely reflected dimensional differences in the fricative groove; these were compared with differences in the spectral moments from the time-aligned acoustic signal.

Method

Participants and Materials

Data for this study were taken from a corpus of recordings made by Sanders (2007). In Sanders' study ten men and ten women between the ages of 18 and 35, with no history of speech problems, oral deformity, or hearing impairment were fitted with palatometer pseudopalates made from their dental impressions. Each passed a hearing screening bilaterally at 500, 1000, 2000, and 4000 Hz at 15 dB HL. An oral mechanism exam was performed to check for dental abnormalities. The participants were instructed to brush their teeth and use mouthwash before placing the pseudopalate in the mouth to reduce any interference with the pseudopalate. The pseudopalate, less than .5 mm thick, extended posteriorly to the back molars and straight across while wires exited the mouth anteriorly between the incisors and connected to a computer system. The participants' speech was then recorded in an Acoustic Industries 7' x 7' single walled sound booth using a head-mounted condenser microphone (AKG C-420) placed 4 cm from the mouth.

Stimuli and Procedures

After the speakers participated in conversation for 30 minutes to allow them to become more accustomed to the presence of the pseudopalate in the mouth, the speakers were asked to repeat three lists of nonsense words ten times each. A total of fifteen consonants were targeted (/t, d, k, g, s, z, n, ʤ, ʧ, ʃ, ʒ, l, r, j, ŋ/) in a VCV context consisting of an initial schwa followed by the target consonant and ending with one of three corner vowels (/i, ɑ, u/). However, /ŋ/ was targeted in VC contexts with the three corner vowels preceding it in order to be representative of English phonological patterns (see appendix). The LogoMetrix palatometric system (LogoMetrix Corporation) recorded the number and location of sensors that were contacted along with acoustic data for each utterance. For the purposes of this study, the fricative /s/ was selected for detailed analysis.

Measurement. The tongue contact and acoustic data were processed with custom software applications created in Matlab (version 6.1) to separate the audio channel from the tongue contact data and to provide detailed spreadsheets that represented palatal contact over time. To acoustically segment the target fricatives, waveforms, and spectral displays were viewed with TF32 software (Milenkovic, 2000). The fricative onset was signified by a rapid increase in zero crossings and spectrographic high frequency energy and a rapid decrease in zero crossings and spectrographic high frequency energy marked the fricative end point. Fricative beginning and end times in seconds were recorded to guide segmentation of the palatometric record.

Because the EPG and acoustic sampling rates differed (acoustic data were collected at a rate of 44.1 KHz and the EPG data were collected at a rate of 48 Hz) and were not automatically aligned by the LogoMetrix software, the EPG frames that most closely corresponded with the fricatives' acoustic beginning and end points were identified manually. To do this, the beginning time of a fricative (in seconds) was divided by the entire length of the file (also in seconds) to determine what percentage of the way through the file the onset of the target sound occurred. Then, using a custom Matlab program that displayed the number of each EPG contact frame and the total number of EPG frames for a token, the acoustic percentage was multiplied by the total number of EPG frames for the token. This identified which EPG frame was the same percentage of the way through the file, thus displaying the tongue-to-palate contact for the fricative onset. To determine what time the target EPG frame occurred, the frame identified using Matlab was then identified using the LogoMetrix software which displayed each frame and the time it occurred in seconds. This same process was used to identify the EPG frame that corresponded with the fricative end. EPG frame numbers and times of occurrence in seconds that corresponded with the onset and offset of the target fricatives were recorded with the corresponding acoustic beginning and end times.

During segmentation 62 tokens showed obvious temporal desynchronization between the acoustic and EPG data (e.g. little to no tongue-to-palate contact at the onset of the fricative) and were discarded. Ten percent of useable data were re-segmented to ensure segmentation accuracy and reliability. The original measurements were then correlated with the resegmented data and were found to be reliable ($r = 1.000$, $p < .001$).

Spectral moments analysis. All tokens were high-pass filtered with a cutoff frequency of 65 Hz. The spectral mean and variance were computed for each token with custom software developed in Matlab. Spectra were derived from 32 cascading 20 ms Hamming windows, the first of which was centered +10 ms after the onset of the fricative. In addition to the 20 ms windows were three 40 ms windows placed at the beginning, middle and end of the fricative (see Figure 1). Note that typically, these 20 ms windows were placed every ten ms and thus had a 50% overlap. However, because these windows occurred twice as often as the EPG frames, the spectral mean and variance were averaged for every two data points and then the average value was aligned with the most closely corresponding EPG frame. Therefore, in Figure 1, the 20 ms windows do not demonstrate a 50% overlap and are a representation of the area from which the average

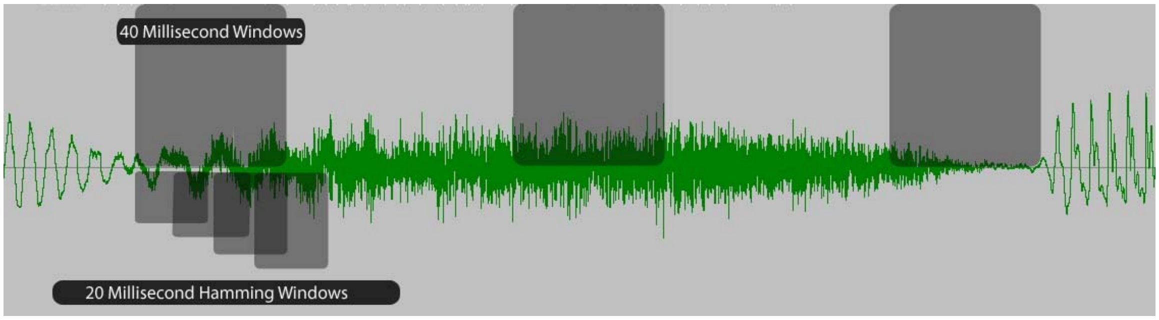


Figure 1. Representation of the spectral moments sampling windows. 40 ms windows were defined at the beginning, middle, and end of the fricative. 20 ms windows were defined every 10 ms for the entire fricative duration.

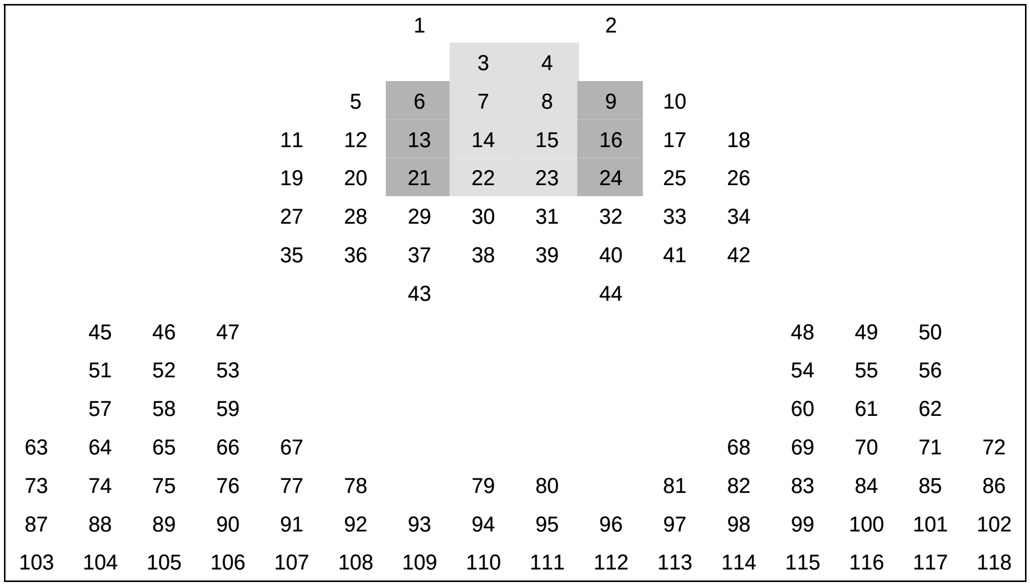
Note. The 20 ms windows were placed every ten ms and thus had a 50% overlap. However, because these windows occurred twice as often as the EPG frames, the spectral mean and variance were averaged for every two data points. Therefore, the representative 20 ms windows in this figure do not demonstrate a 50% overlap.

spectral mean and variance were derived. Spectral measures were made both with and without a cap on the upper frequencies (limiting to 22 kHz). The purpose of a cap in spectral analysis is to limit the influence of high frequency noise that can in some cases influence spectral moment measures.

EPG numerical indices. Custom designed EPG indices, s-narrow, s-wide, and asymmetry were developed for this study to allow a quantitative description of palatal contact changes over time and to provide some detail about contact patterns on specific areas of the pseudopalate for the /s/ fricative groove. Quantitative indices also allow a computation of correlation with the numeric acoustic data.

The s-narrow index quantified palatal contact by using a narrow zone of interest on the anterior portion of the anterior lobe of the pseudopalate where the /s/ fricative groove was expected to appear. This included electrodes located in the four center columns of the anterior lobe of the pseudopalate and extended posteriorly from electrodes three and four (electrodes one and two show labial contact and were excluded) to the fourth row of the anterior lobe of the pseudopalate. The total number of electrodes contacted in the two center columns of the zone was subtracted from the total number of electrodes contacted in the columns on either side of the center columns. Figure 2 depicts the target zone for this index.

The numerical values that this index produced ranged from -1 to 6. Since there were two more electrodes in the center columns, the negative values implied a number of tongue contact scenarios. A negative score could have meant that there was more contact in the center columns than the outer columns (which is not consistent with the production of an /s/ and was not observed) or that the groove was asymmetrical and thus resulted in

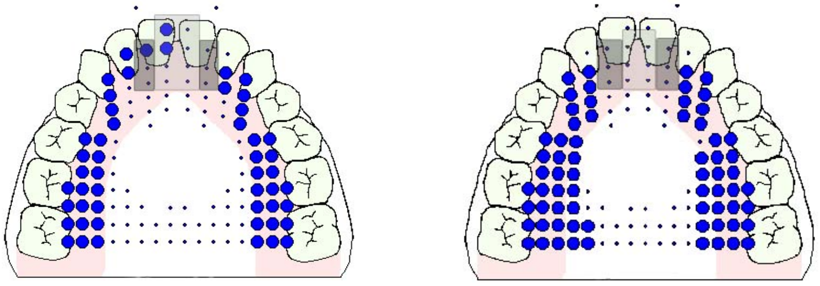


						1			2						
							3	4							
					5	6	7	8	9	10					
				11	12	13	14	15	16	17	18				
				19	20	21	22	23	24	25	26				
				27	28	29	30	31	32	33	34				
				35	36	37	38	39	40	41	42				
						43			44						
	45	46	47									48	49	50	
	51	52	53									54	55	56	
	57	58	59									60	61	62	
63	64	65	66	67							68	69	70	71	72
73	74	75	76	77	78		79	80		81	82	83	84	85	86
87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118

Figure 2. S-narrow EPG index. Numbers represent sensors on the pseudopalate. Lighter shaded areas represent the center electrodes in the target zone and darker shaded areas represent the outer electrodes in the target zone. The number of contacted electrodes in the center columns was subtracted from the number of contacted electrodes in the outer columns to obtain an EPG index score.

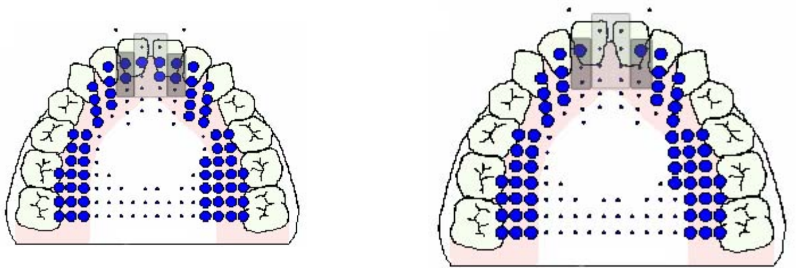
more contact in the center columns (which did occur on a few occasions; see Figure 3 for an example of a negative score due to asymmetrical tongue-to-palate contact). Another possible configuration leading to a negative value could have been that all of the electrodes in the zone were contacted, resulting in complete lingual anterior closure. This would result in a score of -2 and was not observed. However, a small number of tokens did demonstrate complete lingual closure anteriorly, resulting in scores of one and two and implying a lisp. However, misarticulated tokens were discarded before analysis and tokens that appear to have this tongue contact pattern could have had an acoustically correct /s/ with a very small, transient groove that is not apparent in a specific EPG frame (see Figure 3). A score of zero indicated no contact in the target zone and implied that the fricative groove was wider than the target zone (see Figure 3). EPG contact patterns that resulted in scores of one through five could imply wider grooves or narrower grooves and could not be relied on to consistently describe the dimensions of the fricative groove because of the various tongue-to-palate contact patterns that could result in the same numerical score (see Figure 3). However, scores of six could consistently imply a wider fricative groove because the only way to achieve a score of six was for all of the electrodes in the right and left columns to be contacted and for none of the electrodes in the center two columns to be contacted (see Figure 3).

The second index, s-wide, focused on a wider zone of interest on the anterior portion of the anterior lobe of the pseudopalate. The s-wide index included electrodes located in all eight columns of the anterior lobe of the pseudopalate and extended posteriorly from electrodes three and four (once again electrodes one and two were excluded) to the fourth row of the anterior lobe of the pseudopalate. The total



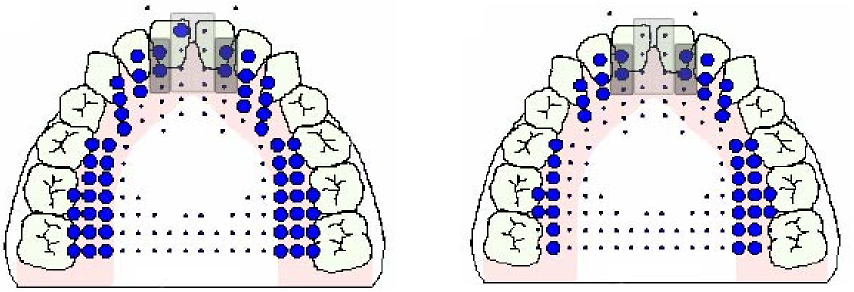
Asymmetrical contact resulting in a score of -1.

Score of 0.



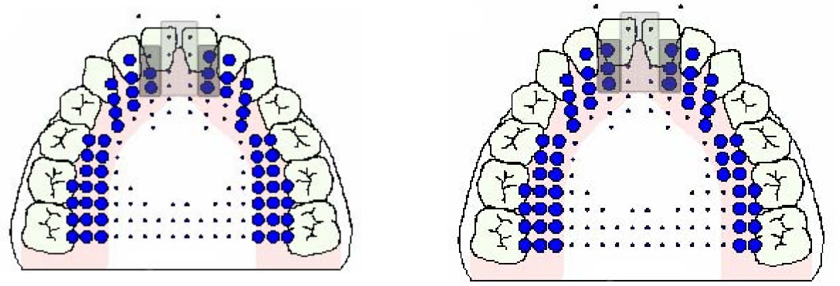
Score of 1. (Complete anterior closure.)

Score of 2.



Score of 3.

Score of 4.



Score of 5.

Score of 6.

Figure 3. Palatal contact patterns and their corresponding s-narrow EPG index values.

number of electrodes contacted in the center four columns of this zone were subtracted from the total number of electrodes contacted in the columns on either side of the center columns (see Figure 4).

The numerical values that the s-wide index produced were zero to ten. Theoretically, negative scores were possible, but none were observed in this data set. A score of zero indicated no contact in the target zone and implied that palatal contact was located posterior to the zone of interest for this index (see figure 5). Similar to the results for the S Narrow index, a number of possible tongue-to-palate contact patterns could occur, resulting in scores of one through ten. Some palatal contact patterns simply show an increase in outer column contact as the index score rises, others show a combination of central and outer column contacts. However, as the scores increase, it is more likely that the tongue contact is mainly in the outer columns (see Figure 5 for examples of differing contact patterns for similar scores).

The various tongue-to-palate contact patterns that could result in the same scores for these indices made it difficult to imply specific details about changes in palatal contact shape over time. These indices were highly experimental and the information they gave about palatal contact shape was crude at best. However, changes in the index scores did denote change in the lingual-palatal contact shape over time and in the future more sensitive, descriptive and reliable indices will need to be developed to describe these changes in more detail.

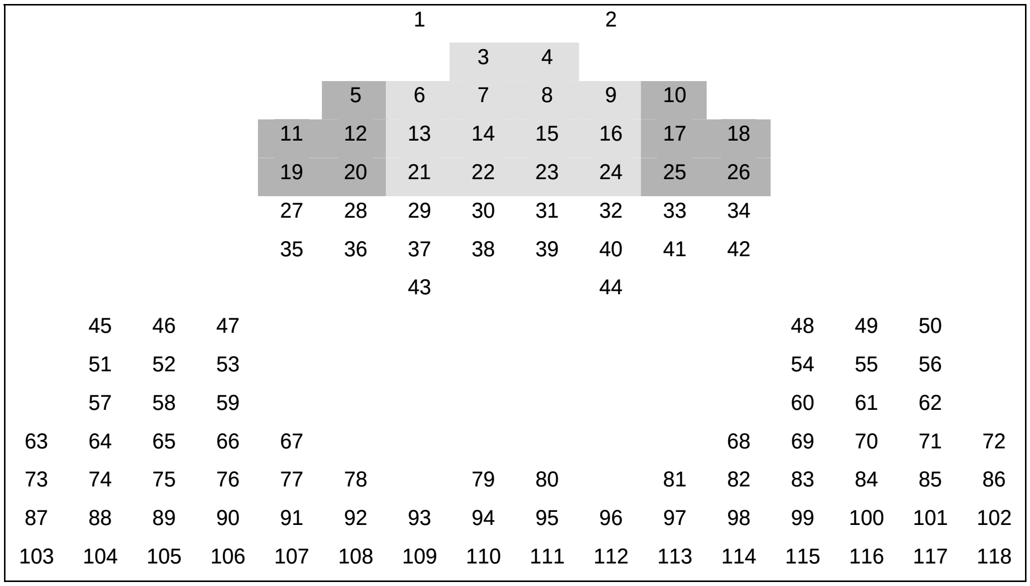
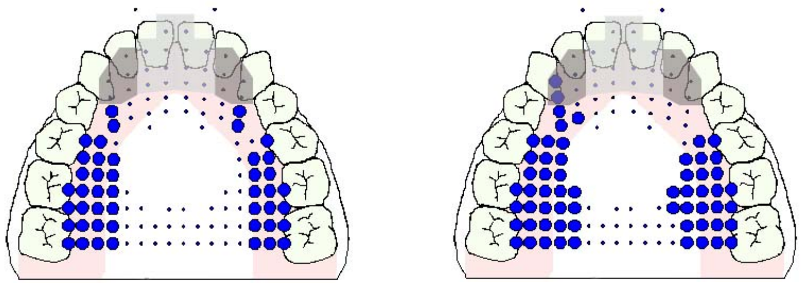
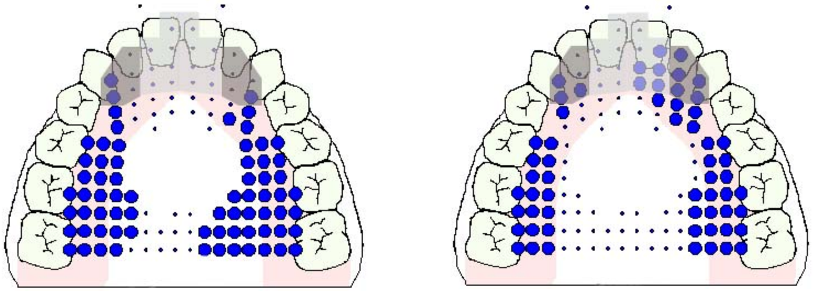


Figure 4. S-wide EPG index. Numbers represent sensors on the pseudopalate. Lighter shaded areas represent the center electrodes in the target zone and darker shaded areas represent the outer electrodes in the target zone. The number of contacted electrodes in the center columns was subtracted from the number of contacted electrodes in the outer columns to obtain an EPG index score.



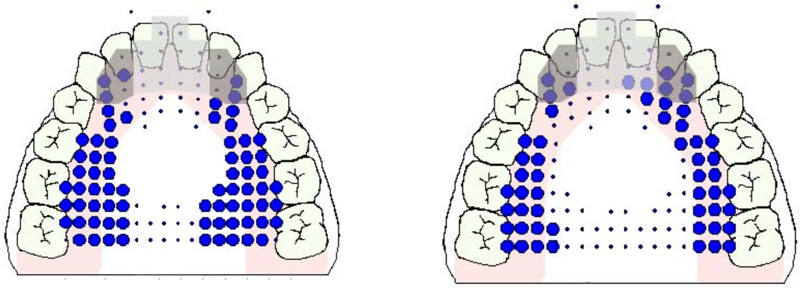
Score of 0.

Score of 2.



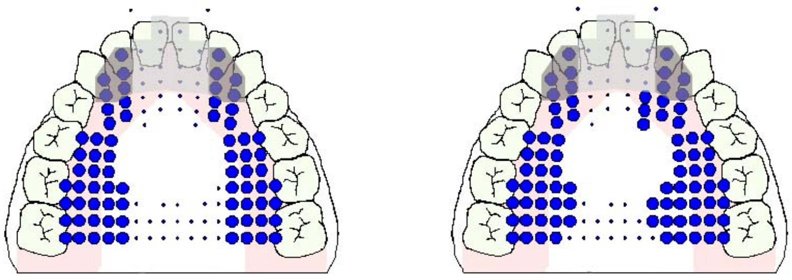
Score of 3.

Score of 3.



Score of 5.

Score of 5.



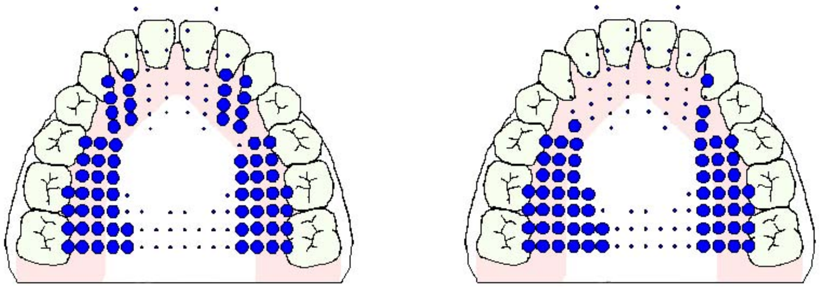
Score of 10.

Score of 10.

Figure 5. Contact patterns for the s-wide EPG index. Similar scores do not equal similar contact patterns.

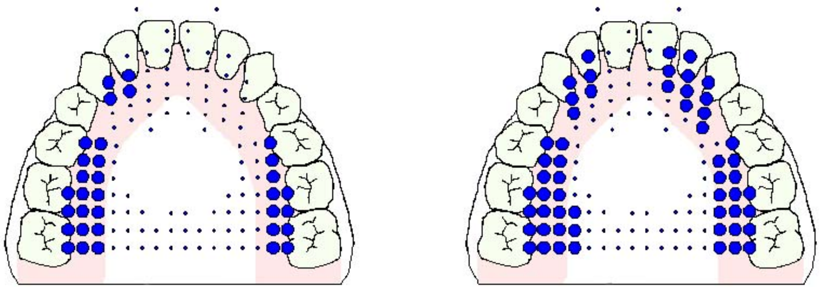
The last index, asymmetry, supplied information regarding the symmetry of palatal contact. It accomplished this by subtracting the contact value for an electrode on the right side of the pseudopalate from the electrode in a mirrored position on the left. Contact values were determined by Matlab with a value of one signifying contact and a value of zero signifying no contact. This index was calculated for the entire anterior lobe of the pseudopalate. Negative asymmetry values indicated more tongue-to-palate contact on the participant's right while positive values indicate more contact on the participant's left (see Figure 6).

Alignment of spectral moment analysis and EPG indices. Once spectral moment analyses and EPG indices were computed, both types of results were aligned to allow for the computation of Pearson correlations between the two methods of analysis. This was done in order to better understand the relationship between changes in the tongue contact patterns and corresponding changes in the acoustic measures of frication. Because the 20 ms spectral moment measures were calculated from windows that occurred twice as often as the frames from the EPG data, the spectral mean and variance were averaged for every two data points and then the averaged value was aligned with the most closely corresponding EPG frame. The most closely corresponding EPG frame was determined by temporally aligning the center of the spectral moment analysis window with the closest EPG frame by matching the time in seconds in each data file. Similarly, the 40 ms spectral moments data were aligned with EPG frames that lined up most closely with the center of each 40 ms window. While aligning the 40 ms spectral moments data with representative EPG frames, it became apparent that in addition to the desynchronized



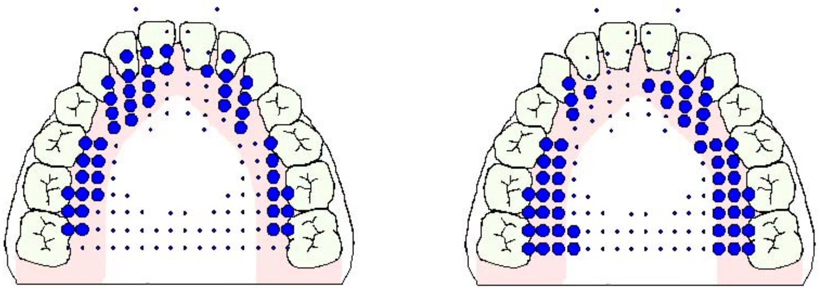
Score of 0.

Score of -2.



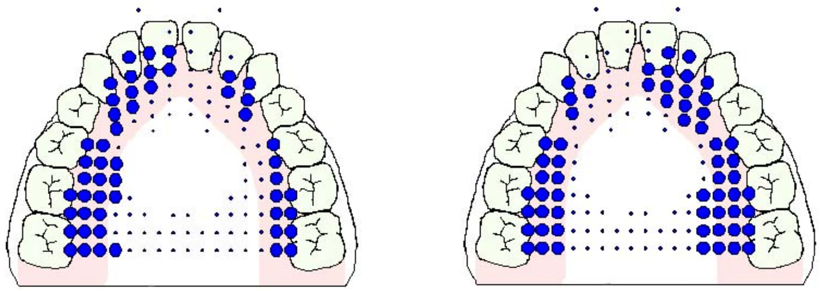
Score of 4.

Score of -5.



Score of 6.

Score of -7.



Score of 8.

Score of -11.

Figure 6. Contact patterns for the Asymmetry EPG index.

tokens identified and discarded during data segmentation, there were several more tokens with less obvious EPG and acoustic desynchronization. These tokens most often displayed little to no palatal contact for the first 40 ms window (which represents the beginning of the fricative). Other tokens displayed little to no palatal contact for the frames that corresponded with the first and second windows and sometimes no contact at all for the frames corresponding with all three windows. These tokens were identified and discarded during acoustic and EPG data alignment. In the end, 232 tokens were analyzed in this study: 104 in the /i/ context, 52 in the /ɑ/ context and 76 in the /u/ context. The reason for the occasional desynchronization is not immediately obvious, but it may have originated as the audio signal was being digitized by the computer’s sound card, whereas the EPG data were streamed to the computer via a USB port. It has recently been learned that future versions of the LogoMetrix acquisition software will stream all data (audio and palatal) via a single USB input, thus fully interlocking the two data channels.

Statistical analysis. Following alignment of the 20 ms and 40 ms spectral moments results and EPG indices for each representative frame, Pearson’s r correlations were computed with SPSS (version 16). Correlations between spectral moments (spectral mean and variance) and EPG indices (s-narrow, s-wide, and Asymmetry) were run for 40 ms and 20 ms data separately, both with and without a cap on the upper frequencies, and for the following groupings: all participants together, male participants alone, and female participants alone. Vowel contexts were examined separately for all groupings.

After analyzing the data for these groupings, some of the strongest correlations for both 20 ms and 40 ms acoustic data were present between s-narrow and spectral mean and variance. Therefore, in order to give a clearer picture of the link between lingual physiology and spectral moments, these variables (s-narrow and spectral mean; and s-narrow and spectral variance) were correlated for each individual speaker to examine in greater detail the specific trends among individuals. Uncapped spectral moments were used because of the high frequency nature of the /s/ fricative; vowel contexts were considered separately for these individual analyses as well.

Results

40 Ms Spectral Moments Results

Group results. For the grouping that included all participants and uncapped spectral moments, weak but significant correlations were found between several variables. Negative correlations demonstrated that as values from EPG indices increased, spectral moment values decreased. Negative correlations were found between s-narrow and spectral variance in the /ɑ/ and /u/ contexts. Positive correlations, showing that that as values from EPG indices increased spectral moment values also increased, were found between asymmetry and spectral mean in the /i/ and /u/ contexts and asymmetry and spectral variance in the /i/ context (see Table 1). Capped spectral moments measures for the same group showed negative correlations between s-narrow and spectral variance in the /ɑ/ vowel context and asymmetry and spectral mean in the /i/ vowel context. A positive correlation between asymmetry and variance in the /i/ vowel context was also observed (see Table1).

For male participants alone and uncapped spectral moments, slightly stronger negative correlations (as EPG index values increased, spectral moments values decreased) were found between s-narrow and spectral variance in the /ɑ/ context. Similarly, slightly stronger positive correlations (as EPG index values increased, spectral moments values increased) were found between asymmetry and mean in the /i/ and /u/ contexts (see Table 1). Capped spectral moments measures for male participants showed negative correlations between s-narrow and spectral variance in the /ɑ/ vowel context and asymmetry and spectral mean in the /i/ vowel context (see Table1).

Table 1

Groups Significant Pearson r Correlations for 40 ms Spectral Moments and EPG Indices

	All Participants						Male Participants						Female Participants					
	/i/		/ɑ/		/u/		/i/		/ɑ/		/u/		/i/		/ɑ/		/u/	
Variables	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
No Cap																		
s-narrow and spectral mean															-.284	.010	-.182	.039
s-narrow and spectral variance			-.222	.005	-.137	.039			-.285	.013								
s-wide and spectral mean																		
s-wide and spectral variance																		
Asymmetry and spectral mean	.250	.001			.208	.002	.311	.001			.220	.029						
Asymmetry and spectral variance	.186	.001											.269	.001				
Capped																		
s-narrow and spectral mean																		
s-narrow and spectral variance			-.236	.003					-.285	.013								
s-wide and spectral mean																		
s-wide and spectral variance																		
Asymmetry and spectral mean	-.211	.001					-.169	.031					-.210	.010				
Asymmetry and spectral variance	.187	.001											.203	.013				

For female participants and uncapped spectral moments, some negative correlations (as EPG index values increased, spectral moments values decreased), different than those found in the grouping of all participants, were found between s-narrow and spectral mean in the /ɑ/ and /u/ contexts. No significant correlations were found between these variables for all participants combined. Additionally, a positive correlation (as EPG index values increased, spectral moments values also increased) between and asymmetry and spectral variance in the /i/ context was found (see Table 1). For capped spectral moments and female speakers, a negative correlation was found between asymmetry and mean in the /i/ context and a positive correlation was found between asymmetry and variance in the /i/ context (see Table 1).

Overall, for the uncapped and capped 40 ms spectral moment data, the s-wide and spectral mean and s-wide and spectral variance combinations did not demonstrate significant correlations for any groupings (all participants, male participants, or female participants). Asymmetry and spectral mean had the most correlations across all groupings. The number of negative correlations equaled the number of positive correlations and the strongest negative correlations for all the participants combined and the male participants were between s-narrow and spectral variance in the /ɑ/ vowel context. However, the strongest negative correlation for the female grouping was between s-narrow and spectral mean (also in the /ɑ/ vowel context). The strongest positive correlations for all the participants combined and the male participants were between asymmetry and spectral mean in the /i/ vowel context while the strongest positive correlation for the female participants was between asymmetry and spectral variance in the /i/ vowel context. Correlations for all groups and variables were weak, but significant. In general, uncapped spectral moments yielded the most correlations (see Table 1).

Individual results. Further analysis focused on s-narrow and spectral mean and variance (spectral moments uncapped) for individual participants and revealed significantly stronger correlations than the large group analyses (see Table 2). Overall, the majority of correlations were negative (as EPG index values increased, spectral moment values decreased) and there were nearly equal counts of significant correlations for both variable combinations (i.e. five correlations between s-narrow and spectral mean and four correlations between s-narrow and spectral variance). The strongest negative correlation was from a female participant's s-narrow and spectral variance combination in the /ɑ/ vowel context. The strongest negative correlation for a male participant was between s-narrow and spectral mean in the /u/ vowel context. Although male participants yielded six significant correlations (including all three vowel combinations), female participants' correlations were stronger and more significant despite there being only three, all of which were in the /ɑ/ vowel context (see Table 2).

20 Ms Spectral Moments Results

Group results. 20 ms uncapped spectral moments with all of the participants' tokens demonstrated several more correlations than the 40 ms uncapped data, but they were similarly weak (see Table 3). Negative correlations (as EPG index scores increased, spectral moment values decreased) were found between s-narrow and spectral variance in all three vowel contexts and s-wide and spectral variance in the /u/ context. Positive

Table 2

Individual Participants' Significant Pearson r Correlations for 40 ms Spectral Measures and the s-narrow EPG Index. Spectral Moments are uncapped

	Male											
	/i/				/ɑ/				/u/			
	Spectral Mean		Spectral Variance		Spectral Mean		Spectral Variance		Spectral Mean		Spectral Variance	
Participants	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Participant 1	-.646	.004										
Participant 2												
Participant 3												
Participant 4												
Participant 5												
Participant 6	.690	.013										
Participant 7			.461	.036								
Participant 8									.628	.029		
Participant 9							-.696	.037				
Participant 10									-.721	.008		
	Female											
Participant 1												
Participant 2							-.751	.000				
Participant 3												
Participant 4												
Participant 5												
Participant 6					-.701	.004						
Participant 7							-.758	.018				
Participant 8												
Participant 9												
Participant 10												

Table 3

Groups Significant Pearson r Correlations for 20 ms Spectral Moments and EPG Indices

	All Participants						Male Participants						Female Participants					
	/i/		/ɑ/		/u/		/i/		/ɑ/		/u/		/i/		/ɑ/		/u/	
Variables	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
No Cap																		
s-narrow and spectral mean																		
s-narrow and spectral variance	-.198	.001	-.201	.001	-.260	.001	-.144	.001	-.246	.001	-.227	.001	-.248	.001	-.186	.003	-.282	.001
s-wide and spectral mean	.089	.003			.137	.001	.146	.001			.231	.001						
s-wide and spectral variance					-.111	.002					-.155	.004						
Asymmetry and spectral mean	.177	.001	.182	.001	.167	.001	.210	.001			.180	.001	.152	.001	.225	.001	.144	.002
Asymmetry and spectral variance							.130	.002					.086	.049				
Capped																		
s-narrow and spectral mean	.186	.001			.219	.001	.145	.001			.114	.033	.190	.001	.207	.001	.271	.001
s-narrow and spectral variance	-.179	.001	-.156	.001	-.238	.001	-.121	.004	-.192	.005	-.206	.001	-.224	.001	-.144	.021	-.257	.001
s-wide and spectral mean					.107	.002			-.150	.027	.172	.001			.185	.003		
s-wide and spectral variance					-.091	.010					-.123	.022						
Asymmetry and spectral mean	-.151	.001	-.231	.001			-.141	.001	-.147	.031			-.127	.003	-.283	.001		
Asymmetry and spectral variance	.090	.003					.123	.003										

correlations (as EPG index values increased, spectral moment values also increased) were found between s-wide and spectral mean in the /i/ and /u/ contexts and asymmetry and spectral mean in all three contexts (see Table 3). Capped spectral moments measures for the same grouping showed correlations in all possible variable combinations. Negative correlations were found between s-narrow and spectral variance in all three contexts, s-wide and spectral variance in the /u/ context, and asymmetry and spectral mean in the /i/ and /ɑ/ context. Positive correlations were found between s-narrow and spectral mean in the /i/ and /u/ contexts, s-wide and spectral mean in the /u/ context, and asymmetry and spectral variance in the /i/ context (see Table 3).

For male participants and uncapped 20 ms spectral moments, negative correlations were found between s-narrow and spectral variance in all three vowel contexts and s-wide and spectral variance in the /u/ context. Positive correlations were found between s-wide and spectral mean in the /i/ and /u/ contexts, asymmetry and spectral mean in the /i/ and /u/ contexts, and asymmetry and spectral variance in the /i/ context. Capped 20 ms spectral moments measures for male participants showed negative correlations between s-narrow and spectral variance in all contexts, s-wide and spectral mean in the /ɑ/ contexts, s-wide and spectral variance in the /u/ context, and asymmetry and spectral mean in the /i/ and /ɑ/ context. Positive correlations were shown between s-narrow and spectral mean in the /i/ and /u/ contexts, s-wide and spectral mean in the /u/ context, and asymmetry and spectral variance in the /i/ context (see Table 3).

For female participants and uncapped 20 ms spectral moments negative correlations (as EPG index scores increased, spectral moment values decreased) were found between s-narrow and spectral variance in all three vowel contexts. Positive correlations (as EPG index values increased, spectral moment values also increased) were found between and asymmetry and spectral mean in all contexts and asymmetry and spectral variance in the /i/ context (see Table 3). For capped 20 ms spectral moments and female participants, negative correlations were found between s-narrow and spectral variance in all contexts and asymmetry and spectral mean in the /i/ and /ɑ/ contexts. Positive correlations were found between s-narrow and spectral mean in all contexts and s-wide and spectral mean in the /ɑ/ context (see Table 3).

On the whole, for the uncapped and capped 20 ms spectral moment data, all combinations of the spectral moments and EPG indices resulted in at least some significant correlations across all vowel contexts and participant groupings. S-narrow and spectral variance had the most correlations across all groupings. There were also nearly as many positive correlations as negative (26 positive, 29 negative). The strongest negative correlations for all the participants combined and the male participants were between s-narrow and spectral variance. However, the strongest negative correlation for all the participants combined was in the /u/ vowel context and the strongest male negative correlation was in the /ɑ/ vowel context. The female participants differed in that their strongest negative correlation was between asymmetry and spectral mean in the /ɑ/ vowel context. Interestingly, the strongest positive correlation for all the participants combined and female participants was between s-narrow and spectral mean in the /u/ vowel context. The strongest positive correlation for the male participants was between s-wide and spectral mean in the /u/ vowel context. Therefore, when using the 20 ms spectral moments data for analysis, the male participants' positive correlations differed from the patterns seen for all the participants combined as well as the female participants. This contrasts with the female participants' differing patterns when using the 40 ms spectral moments for analysis.

In general, the 40 ms and 20 ms spectral moments gave somewhat differing results for both large group and individual data. For large group data, the 20 ms spectral moments showed more correlations than the 40 ms spectral moments. Additionally, the 20 ms data revealed that there were more negative than positive correlations and that s-narrow and variance was the most frequently occurring correlation (the 40 ms data showed equal numbers of positive and negative correlations and that asymmetry and spectral mean was the most frequently occurring correlation). 20 ms results also showed that the strongest positive correlations were for females and all participants rather than males and all participants, which was the conclusion from the 40 ms data. For the 20 ms data, capped spectral moments yielded more correlations, but the opposite was true for 40 ms data. However, as was the case with 40 ms spectral moments analysis, the correlations for all groups and variables using 20 ms spectral moments were weak but significant. (See Table 3 for statistics and Table 4 for more detailed information regarding the differences in 40 and 20 ms large group results.)

Individual results. Further analysis focused on s-narrow and 20 ms spectral mean and variance (spectral moments uncapped) for individual participants and revealed several more and much stronger correlations than were found in the 40 ms individual participants analysis. 20 ms spectral moments analyses also revealed that s-narrow and

Table 4

40 ms and 20 ms Large Group Results Comparison

Comparison	40 ms Data	20 ms Data
In general		More correlations found than in the 40 ms data
Variables without correlations	S-wide and spectral mean S-wide and spectral variance	None
Most frequent correlations	Asymmetry and spectral mean	S-narrow and spectral variance
Amount of negative and positive correlations	13 of each	29 negative, 26 positive
Strongest negative correlations	All participants and male participants: s-narrow and spectral variance, /ɑ/ vowel context Female participants: s-narrow and spectral mean, /ɑ/ vowel context	All participants and male participants: S-narrow and spectral variance, /u/ vowel context for all participants combined, /ɑ/ vowel context for male participants Female participants: Asymmetry and spectral mean, /ɑ/ vowel context
Strongest positive correlations	All participants and male participants: asymmetry and spectral mean, /i/ vowel context Female participants: asymmetry and spectral variance, /i/ vowel context	All participants and *female* participants: s-narrow and spectral mean, /u/ vowel context *Male* participants: s-wide and spectral mean, /u/ vowel context
Strength of correlations	Weak but significant	Weak but significant
More correlations in capped or uncapped data	Uncapped yielded more correlations	Capped yielded more correlations

spectral variance was the most frequently occurring correlation (40 ms data reported s-narrow and spectral mean). The strongest negative correlation was for a female participant between s-narrow and spectral variance in the /ɑ/ vowel context (similar to the 40 ms results). The strongest negative correlation for a male participant was between s-narrow and variance (this differs from the 40 ms data) in the /u/ vowel context (this is similar to the 40 ms data). There was nearly the same count of correlations for female participants (22) as male participants (23). However, the overall results were similar to those found in the 40 ms data analysis in that the majority of correlations were negative, the /ɑ/ vowel context led to most of the strongest correlations, and female participants generally had stronger correlations than the males (see Table 5 for statistics and Table 6 for a comparison of 20 ms and 40 ms individual spectral moments results).

Illustrative Cases

A few of the individual participants' correlations and tongue-to-palate contact pattern trends were of special interest because of what they revealed about the link between the EPG and acoustic measures. These are described below.

Case One. The first case was a female participant who demonstrated the strongest 40 ms correlation, which was between the variables s-narrow and spectral variance in the /a/ vowel context ($r = -0.758$, $p < 0.018$). Her three useable repetitions (other repetitions were eliminated due to desynchronization of the EPG and acoustic signals) demonstrated a clear inverse relationship between s-narrow values and spectral variance. As the s-narrow values increased, the spectral variance decreased (see Figure 7). Individual frames of her palatal contact patterns for these three repetitions showed narrower grooves in the

Table 5

Individual Participants' Significant Pearson r Correlations for 20 ms Spectral Measures and the s-narrow EPG Index (Spectral moments are uncapped)

	Male											
	/i/				/ɑ/				/u/			
	Spectral Mean		Spectral Variance		Spectral Mean		Spectral Variance		Spectral Mean		Spectral Variance	
Participants	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Participant 1							-.521	.022				
Participant 2	-.325	.002	-.265	.012					-.505	.003	-.446	.009
Participant 3	-.364	.009	-.283	.046			-.413	.023			-.616	.001
Participant 4	.278	.024					-.407	.015			.328	.005
Participant 5	.418	.004										
Participant 6												
Participant 7					-.501	.048					-.306	.043
Participant 8									.325	.033	-.367	.016
Participant 9			-.427	.006			-.482	.015				
Participant 10	-.409	.003	-.418	.003			-.517	.034	-.469	.002		
	Female											
Participant 1											-.406	.021
Participant 2			-.482	.031			-.412	.002	.334	.018	-.343	.015
Participant 3			-.340	.003	.600	.014			.326	.038	-.318	.043
Participant 4			-.461	.003					-.420	.023		
Participant 5					-.722	.000	.405	.045				
Participant 6											-.328	.006
Participant 7			-.341	.003			-.588	.000			-.565	.002
Participant 8												
Participant 9							-.569	.011				
Participant 10			-.433	.000			-.797	.006	.267	.024	-.437	.000

Table 6

40 ms and 20 ms Individual Participants' Results Comparison (Spectral moments are uncapped)

Comparison	40 ms Data	20 ms Data
In general		More correlations found than in the 40 ms data
Strength of correlations compared with larger groupings	Stronger correlations than those found in larger groupings	Stronger correlations than those found in larger groupings
Variables without correlations	None	None
Most frequent correlations	S-narrow and spectral mean: 5 S-narrow and spectral variance: 4	S-narrow and spectral variance: 30 S-narrow and spectral mean: 15
Amount of negative and positive correlations	6 negative, 3 positive	36 negative, 9 positive
Strongest negative correlations	Female: s-narrow and spectral variance, /ɑ/ vowel context Male: s-narrow and spectral mean, /u/ vowel context	Female: s-narrow and spectral variance, /ɑ/ vowel context Male: Asymmetry and spectral *variance*, /u/ vowel context
Strength of correlations	Although there were only three significant correlations for female participants, their correlations were stronger and more significant All female correlations were in the /ɑ/ vowel context	Female participants had the strongest correlations All of the female participants' strongest correlations were in the /ɑ/ vowel context There were roughly the same number of correlations for males (23) and females (22)

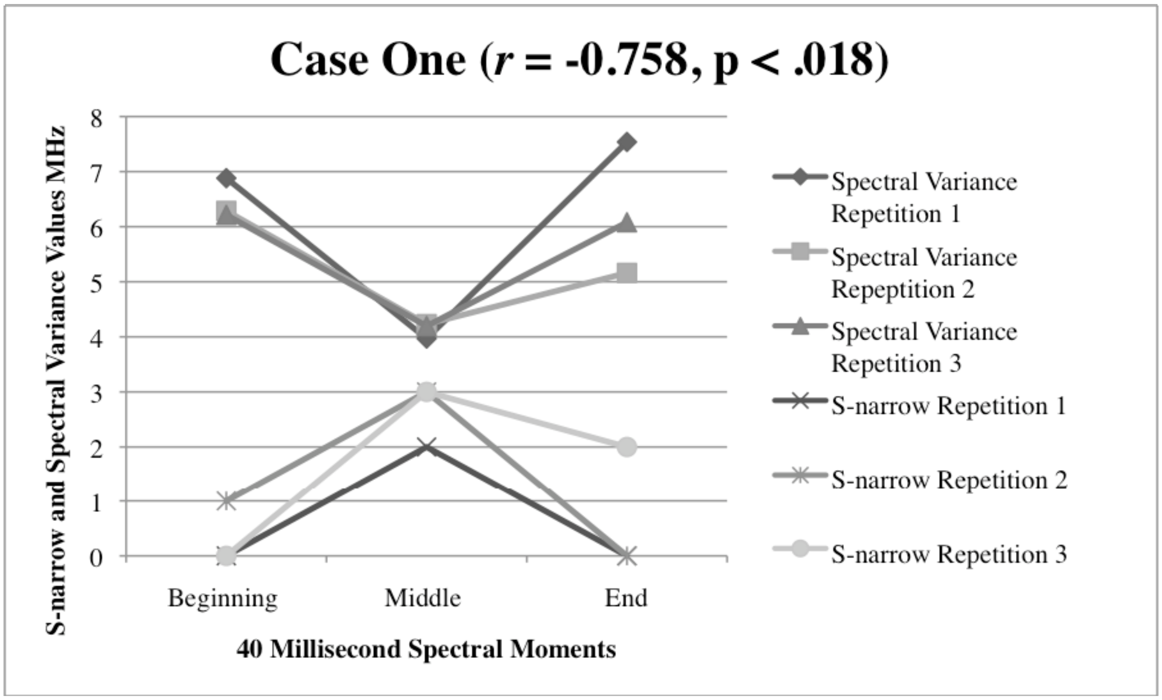


Figure 7. Illustrative case number one. Spectral variance values are reported in megahertz values (MHz) for ease in graphing.

middle frames for each repetition. These frames were also when the s-narrow values increased and the spectral variance decreased (see Figure 8). Other participants demonstrated similar trends but not as clearly as this speaker.

Case Two. The second case was a male participant who demonstrated the highest 40 ms correlation, which was between the variables s-narrow and spectral mean in the /u/ vowel context ($r = -0.721$, $p < 0.008$). His four useable repetitions demonstrated a similar inverse relationship between s-narrow and spectral mean. However, this participant's first two repetitions demonstrated a different direction of movement than the last two. During the first two repetitions, the s-narrow values increased and the spectral mean decreased and during the last two repetitions s-narrow values decreased and the spectral mean increased (see Figure 9). Additionally, his palatal contact patterns for the first two repetitions showed wider grooves at the onset of the fricative moving to a narrower groove at the offset while the contact patterns for the last two repetitions showed a narrower groove at the onset of the fricative moving to a narrower groove at the offset (see Figure 10).

Case Three. The third case was a male participant with the strongest positive correlation between the variables s-narrow and spectral mean in the /i/ context ($r = 0.690$, $p < 0.013$). This speaker's first repetition showed a groove wider than the s-narrow index, resulting of a score of zero for each frame and should be disregarded. In general, this speaker's tongue contact patterns showed a widening of the fricative groove and less palatal contact by the end frame of each repetition (except the first) that coincided with a decrease in spectral mean (see Figures 11 and 12).

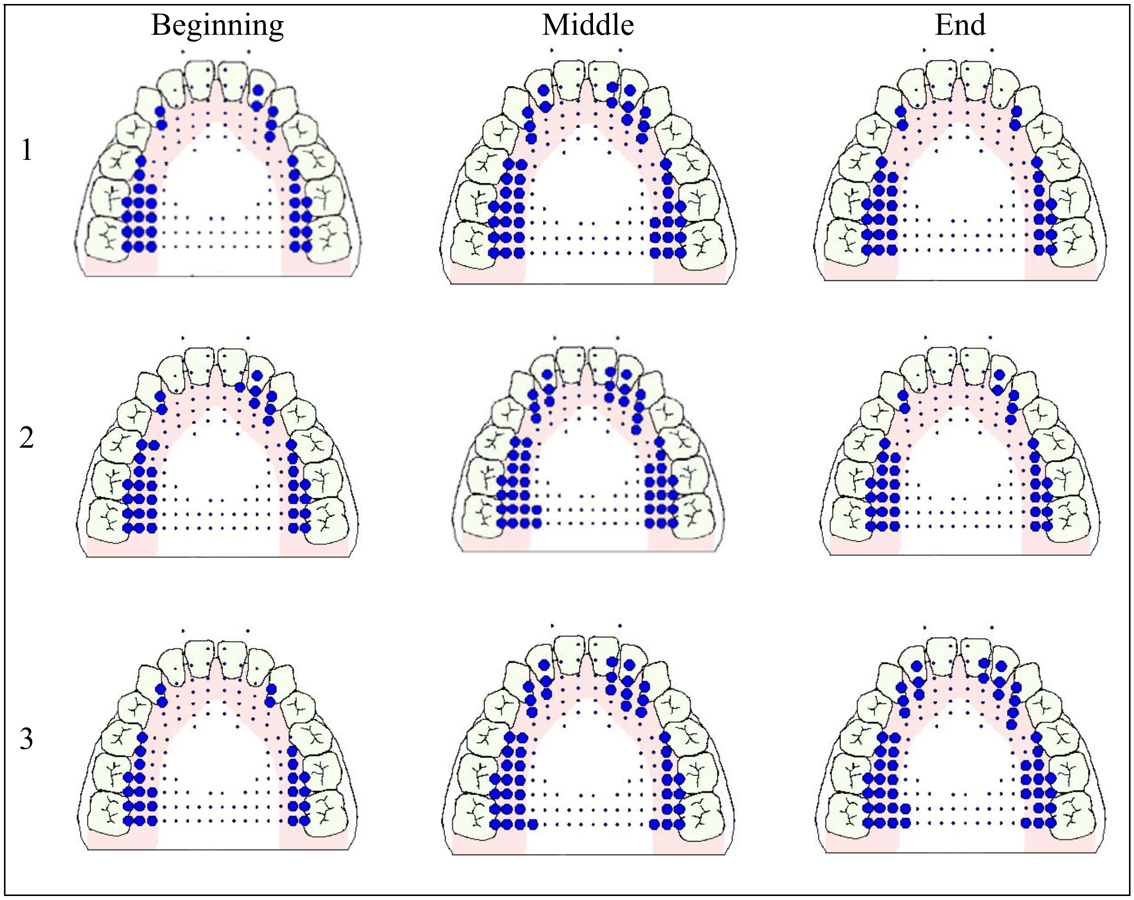


Figure 8. Tongue-to-palate contact patterns for case one. Rows represent repetitions, columns represent the frames that align with the beginning, middle, and end 40 ms acoustic windows.

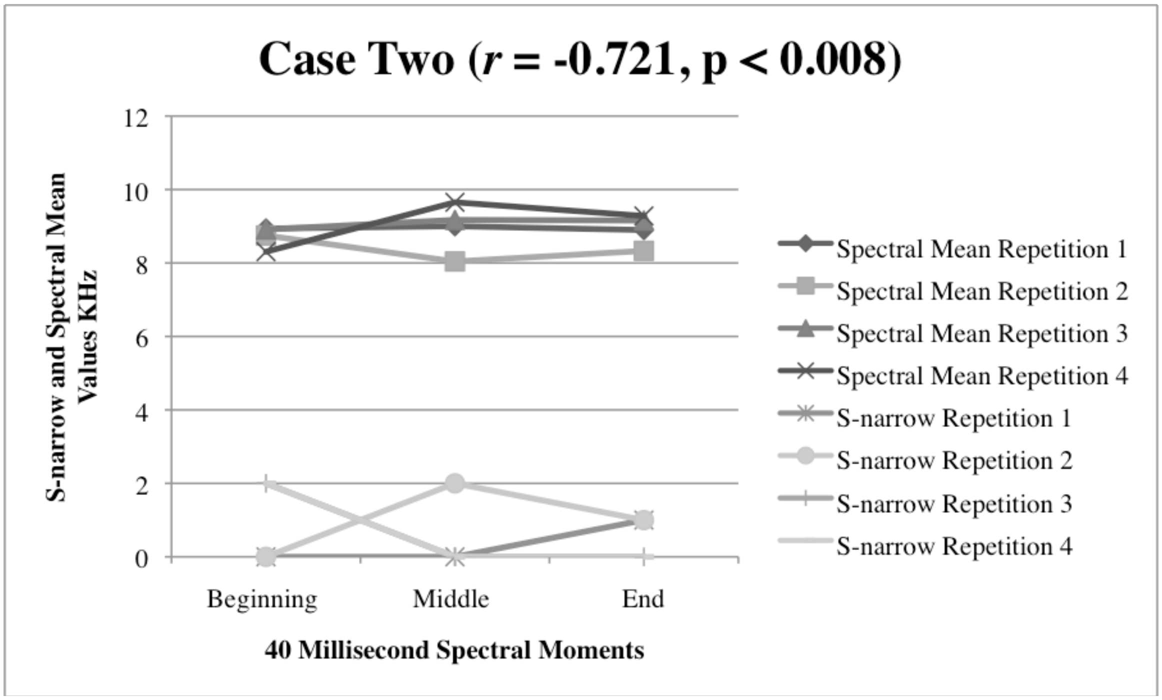


Figure 9. Illustrative case number two. Spectral mean values are reported in kilohertz values (KHz) for ease in graphing.

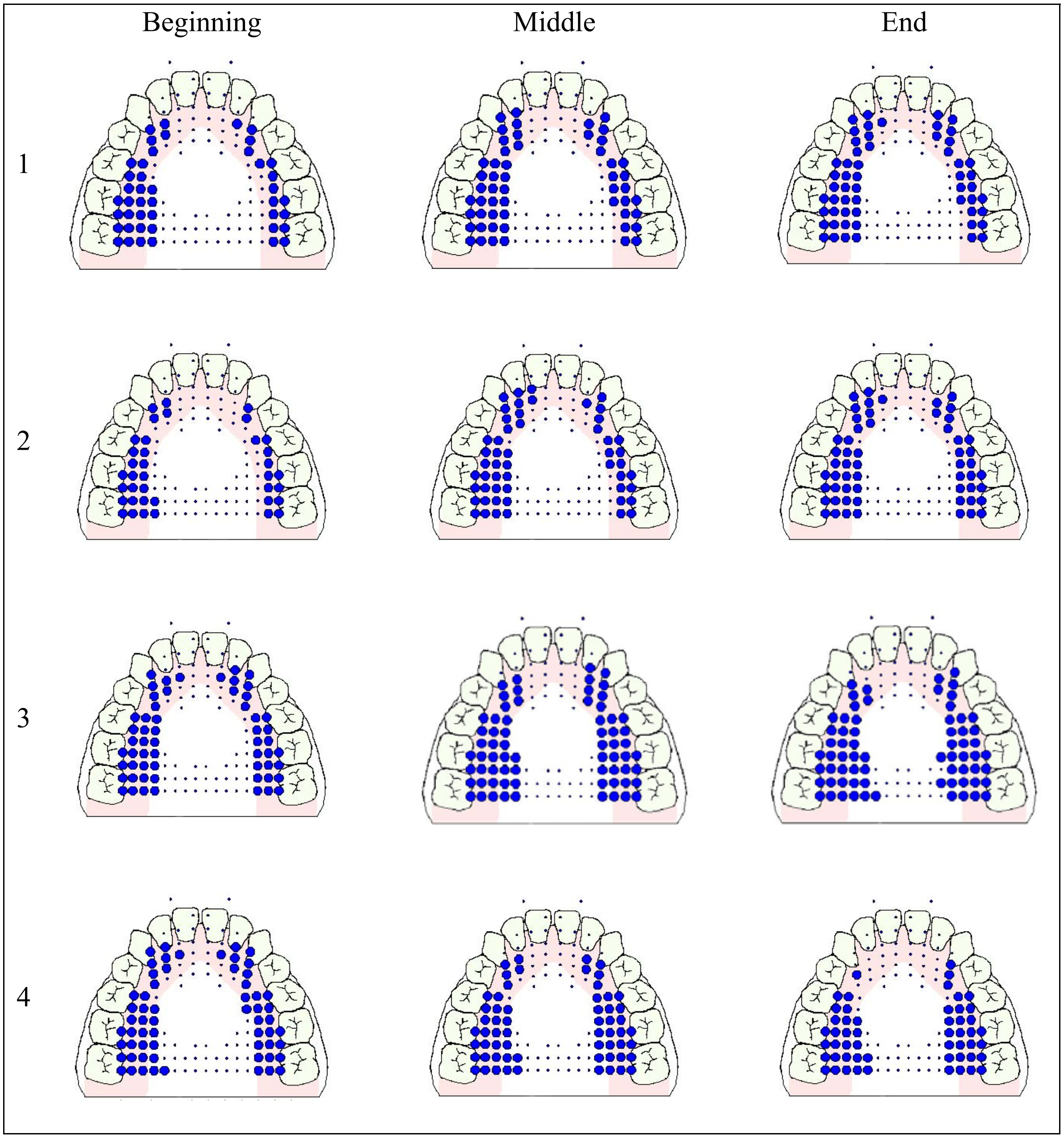


Figure 10. Tongue-to-palate contact patterns for case two. Rows represent repetitions, columns represent the frames that align with the beginning, middle, and end 40 ms acoustic windows.

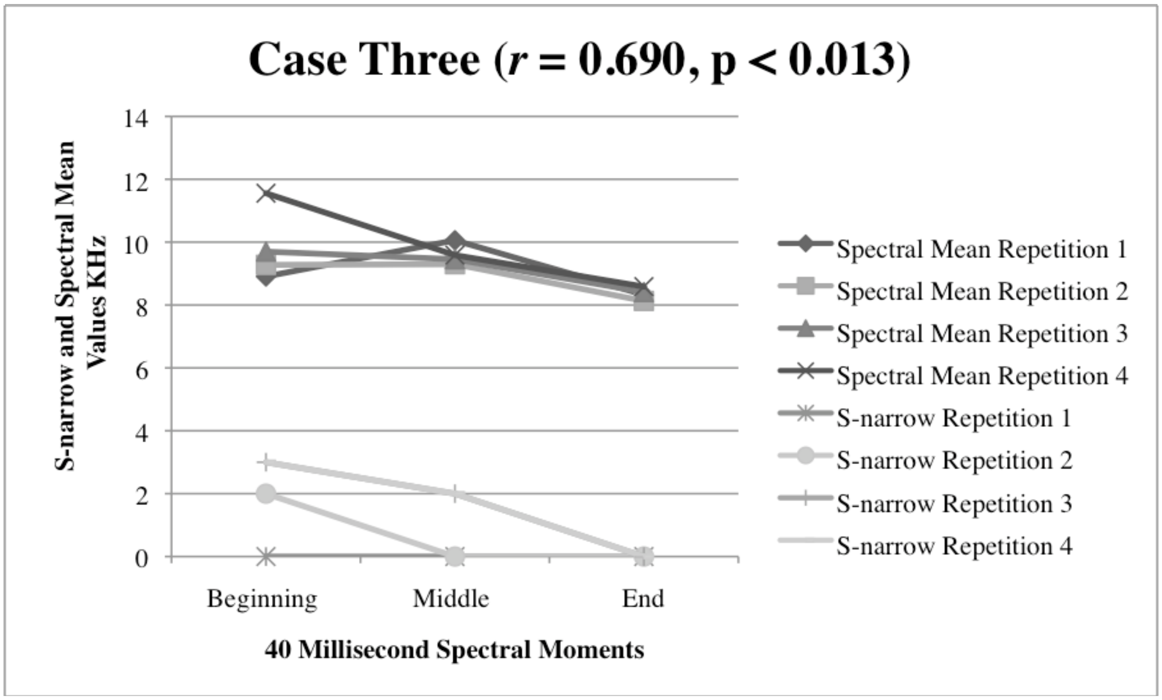


Figure 11. Illustrative case number three. Spectral mean values are reported in kilohertz values (kHz)for ease in graphing.

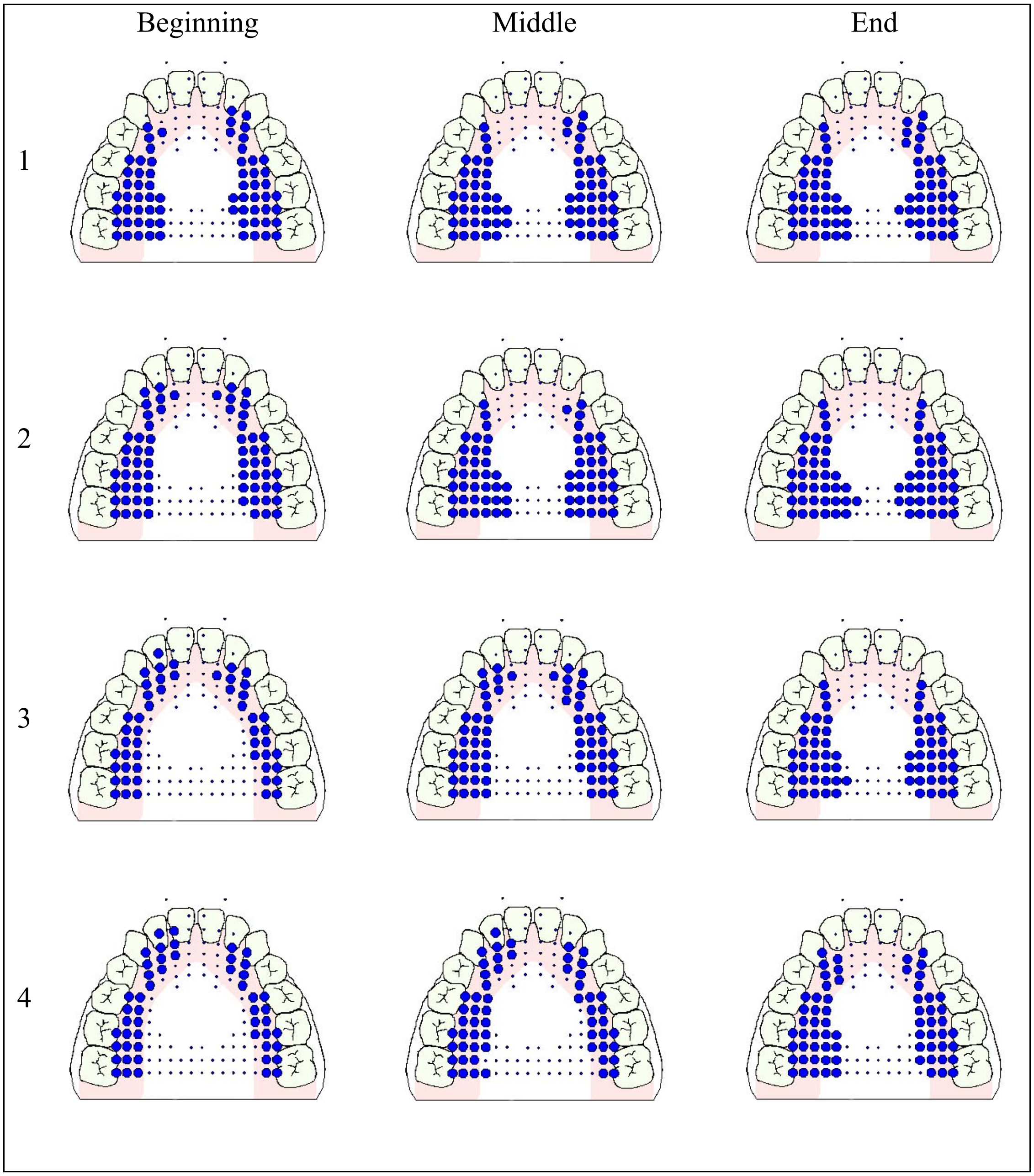


Figure 12. Tongue-to-palate contact patterns for case three. Rows represent repetitions, columns represent the frames that align with the beginning, middle, and end 40 ms acoustic windows

Case Four. This participant was a female who did not demonstrate a significant correlation between s-narrow and spectral mean (see Figure 13) but her palatal contact patterns are worthy of closer examination. All but the fourth repetition start with a narrower groove at the fricative onset and moved to a wider groove than at the offset. The fourth repetition showed that at the fricative onset the groove was fairly wide and changed to a narrower groove by the end of the fricative (see Figure 14). Both of these patterns are seen in Case Two, but for this participant, starting the fricative with a wider groove appeared to be the most common pattern.

Case Five. This was a female participant whose 20 ms uncapped correlation for s-narrow and spectral variance in the /ɑ/ vowel context was the strongest ($r = -0.797$, $p < 0.006$). She demonstrated an inverse relationship between the two variables in that as s-narrow values increased, spectral variance decreased (see Figure 15). However, because of the increased number of data points that are used in the 20 ms spectral moments analysis, it is clear that the most changes occurred at the onset and end of the fricative. Her palatal contact patterns showed a well-formed groove in place at the onset of the fricative with movement towards a wider groove by the end of the fricative, similar to the contact patterns seen in Case Three (see Figure 16).

Case Four ($r = 0.327, p < .186$)

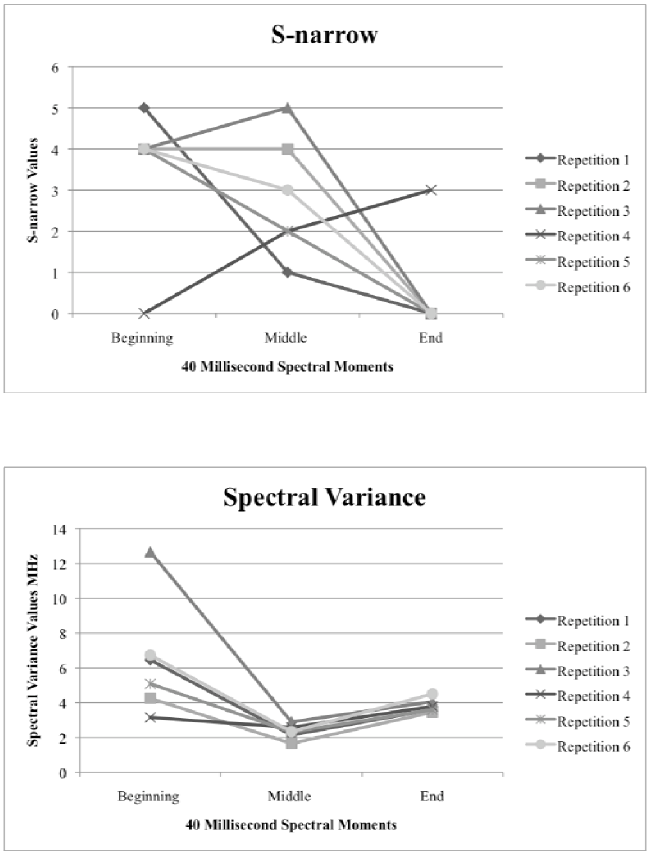


Figure 13. Illustrative case number four. Spectral variance values are reported in megahertz values (MHz) for ease in graphing. S-narrow and spectral variance are graphed separately for clarity.

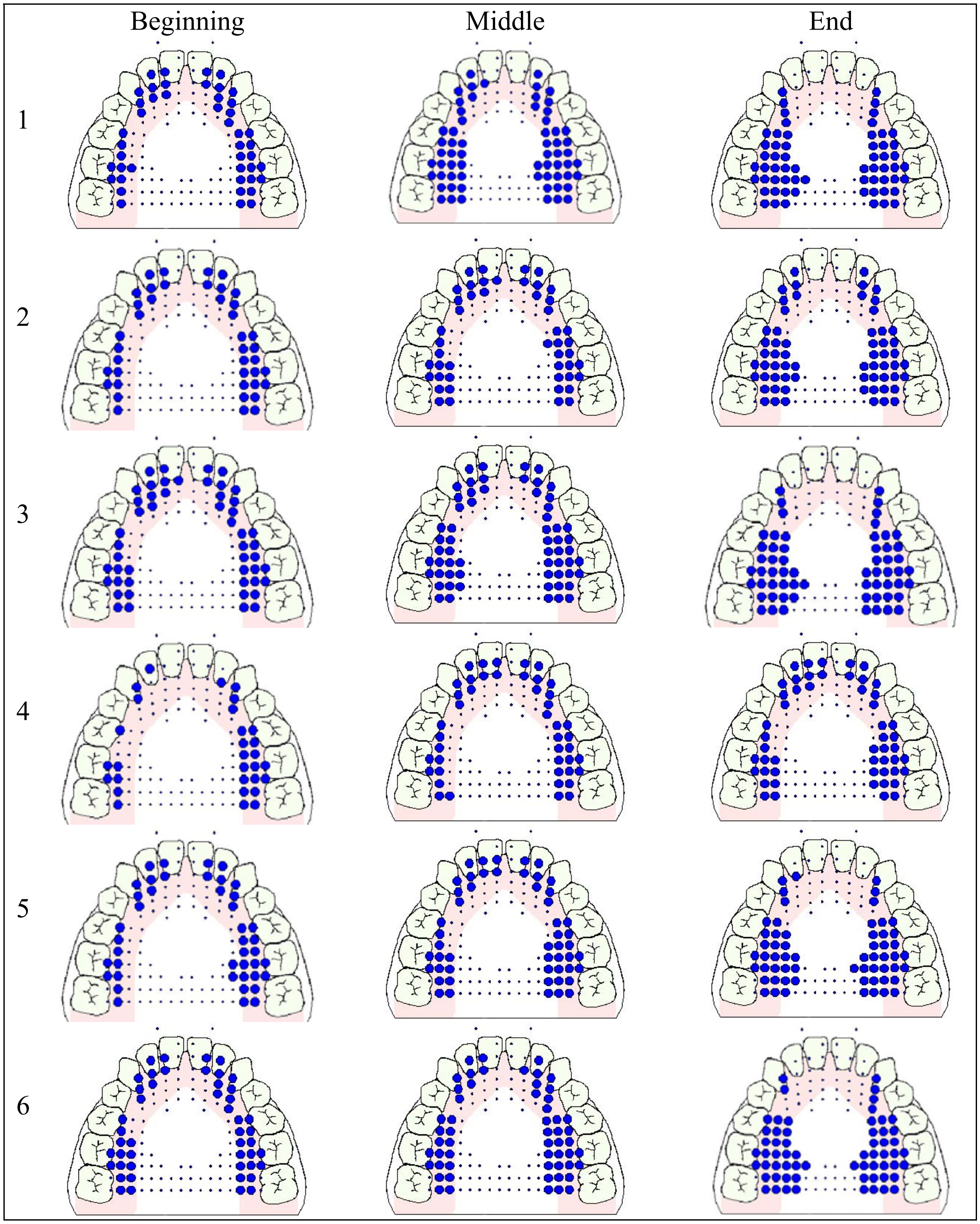


Figure 14. Tongue-to-palate contact patterns for case four. Rows represent repetitions, columns represent the frames that align with the beginning, middle, and end 40 ms acoustic windows.

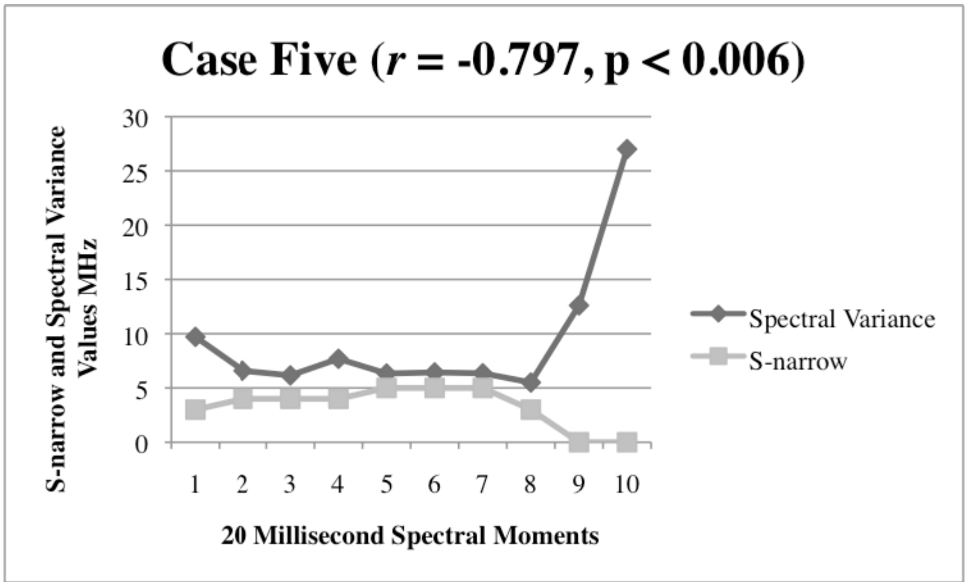


Figure 15. Illustrative case number five. Spectral variance values are reported in megahertz values (MHz) for ease in graphing.

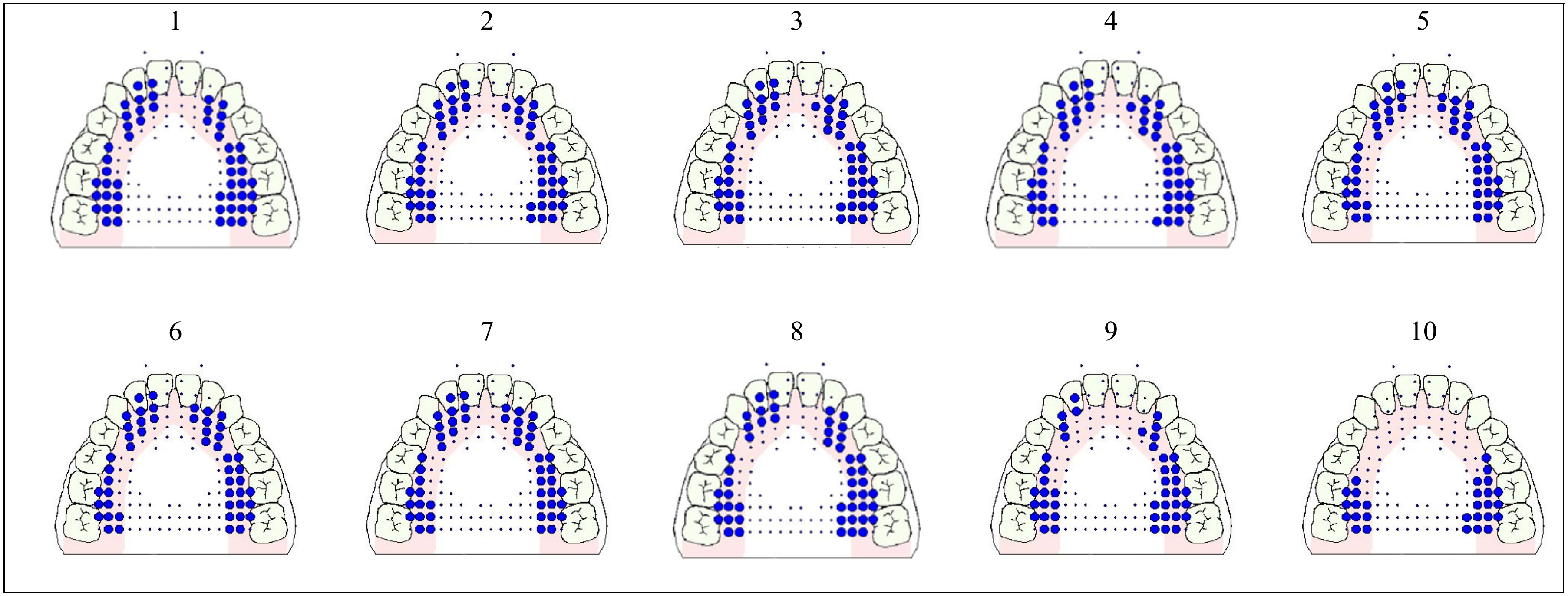


Figure 16. Tongue-to-palate contact patterns for case five. Columns represent the frames that align with the ten 20 ms windows. Only one repetition was usable and is presented above.

Discussion

A number of limitations make it difficult to infer clear causal links between articulatory contact patterns and their acoustic results. One limitation lies in the nature of correlational studies, because correlation does not necessarily reflect causation. Secondly, the relative insensitivity of the s-narrow EPG index to varying tongue contact patterns makes it difficult to accurately describe the frication groove from this relatively crude numerical representation. Finally, there is the problem of sensitivity of the spectral moment measures to noise. However, despite these limitations, it is clear from the results of this study that changes in tongue contact patterns (as noted by changes in EPG index values) are in many cases systematically associated with changes in spectral mean and variance.

40 and 20 ms Results

Large group spectral moments. It is difficult to identify reliable trends for groups of speakers because of differences in the results of the 40 ms and 20 ms spectral moments data sets and differences in the results of capped and uncapped spectral moments (see Tables 1 and 3). The 40 ms spectral moments analysis for groups of speakers may have resulted in fewer correlations than the 20 ms spectral moments because there were several more windows used in the 20 ms analysis which would allow for a clearer picture than that available with just three 40 ms windows. This may also be another explanation for why the 40 ms data did not show any significant correlations between s-wide and spectral mean or variance. Additionally, differences between capped and uncapped data for both 40 ms and 20 ms data were most likely due to the sensitivity of spectral measures to noise in the acoustic signal.

The correlations found in both the 40 ms and 20 ms group data sets were similarly weak compared to the stronger correlations found when examining individual speakers. This could have been due to inter- and intra- speaker palatal contact variability that may or may not have been represented in the acoustic signal. Remember that Hoole et al. (1993) found that for three of their six participants, coarticulatory patterns seen in the EPG data were not manifest in the acoustic data. The same articulatory-to-acoustic mismatch could have been present in both the 40 and 20 ms group data sets, thus contributing to the overall weakness of these correlations.

However, the correlations found for both 40 and 20 ms spectral moments and EPG indices were highly significant, despite the ambiguity of the EPG index and sensitivity of spectral measures. Future studies that improve tongue-to-palate contact pattern quantification methods may be able to more clearly describe specific trends among groups of speakers.

Individual spectral moments. Both the 40 ms and 20 ms spectral moments results for individuals resulted in some interesting findings. Although the 40 ms results showed one more correlation between s-narrow and mean than between s-narrow and variance, the 20 ms results revealed that the majority of correlations were between s-narrow and spectral variance. This discrepancy could again be due to the greater detail that 20 ms spectral analysis provides. However, both 40 and 20 ms analyses revealed that the majority of correlations found were negative. The correlations in these data sets were much stronger than the 40 and 20 ms group analyses and may allow more confident inferences about tongue-to-palate contact patterns and their relationship with spectral moments. It seemed that in general, as the EPG index s-narrow increased, spectral mean and variance decreased. This trend was also observed in some of the illustrative cases discussed below.

Another interesting trend seen in both the 40 ms and 20 ms individual analyses was that female participants had the strongest correlations, all of which were in the /a/ context. This could be because female participants may be more consistent in their productions of /s/ in the /ɑ/ context than male participants. However, this contrasts with Sanders' (2007) study of variability in which she concluded that no gender effects could be confidently stated because of the risk of a type 1 error. Sanders also concluded that for the phonemes /r/, /l/, and /s/ the /ɑ/ vowel context resulted in the most variable performance. Therefore, the reason for the female speakers' strong correlations within the /ɑ/ vowel context remains unclear.

Illustrative Cases

Case One. Case One's clear inverse relationship between s-narrow and spectral variance suggests, at least for this participant, that a narrowing of the fricative groove decreased spectral variance. This could be because a narrower constriction could produce a narrower bandwidth of noise with less spectral variance.

Case Two. Case Two also demonstrated a similar relationship, but between s-narrow and spectral mean. For this participant, as the lingual groove narrowed, spectral mean values decreased. His results were also of special interest because half of his tokens displayed differing directions (the first two tokens had wider grooves which changed to more narrow grooves by the end of the fricative and vice versa for the last two tokens). Furthermore, note that fricative narrowing in the middle frames was not as distinct as it was for case number one, but this participant still demonstrated the same inverse relationship of decreasing spectral mean when the grooves were narrower, regardless of whether the narrower frames were at the beginning or end of the fricative. Therefore, spectral mean and variance may be useful in tracking lingual changes in fricative groove dimensions, although it must be recognized that motor equivalence could contribute ambiguity to the interpretation of the acoustic data.

Case Three. Case Three was a male participant with the highest positive correlation for the 40 ms spectral moments data. The trend seen in his four repetitions in the /i/ context (the first repetition EPG contact patterns all received scores of zero on the s-narrow EPG index, and thus must be discarded) was that as the s-narrow values decreased the groove widened (see Figure 12) and spectral mean also decreased. This is in direct contrast to the patterns seen in Case Two which suggest that as the groove widens spectral mean should increase. The cause for this discrepancy is not known.

Case Four. The tongue-to-palate contact patterns seen in Case Four, despite the lack of a significant correlation, provide interesting insight into coarticulation and individual variability. For the majority of this participant’s onset EPG frames, a narrow groove was already in place. However, several repetitions for cases one, two, and three had wider grooves at the fricative onset. Furthermore, this participant was fairly consistent in her production of a narrow groove at the onset of the fricative in that five out of her six repetitions began this way. This participant’s early formation of a narrow groove, and her deviation from it in one repetition, could be merely idiosyncratic or could give a glimpse into the variability of speakers’ tongue-to-palate contact patterns and possible effects of coarticulation on tongue-to-palate contact patterns.

Case Five. Case Five demonstrated a similar correlation to case one—an inverse relationship between s-narrow and spectral variance in the /ɑ/ vowel context. The added sampling windows for this participants’ 20 ms spectral moments showed that although the relationship is similar to that of case one, the most changes occur at the onset and offset of the fricative. The greatest difference between s-narrow and spectral variance occurs in the last few frames as the fricative groove widens and spectral variance increases. These windows, where the greatest tongue contact and acoustic changes are taking place, provide more insights into the relationship between the palatometric and acoustic variables than where both are relatively stable during the middle of the fricative. Considering the /ɑ/ vowel context following the /s/ in this token, the dramatic changes at the end of this fricative are likely due to coarticulation.

Limitations

Several difficulties were encountered during this study which limit the generalization of its findings. First, the LogoMetrix palatometer software, while useful for therapeutic purposes, does not lend itself well to the precise alignment of EPG and acoustic data. Not only are the acoustic data recorded at a much higher rate (44.1kHz) than the EPG contact patterns (48 Hz), the acoustic data and EPG data are stored in separate channels, which made accurate aligning the EPG frames to specific acoustic events difficult. It became apparent throughout the data segmentation and alignment processes that the software had alignment difficulties and in the end 38.7% of the original data appeared to be correctly synchronized. This problem should not be an issue in the near future because a newer version of a palatometer is scheduled to be released which automatically aligns the EPG and acoustic data.

A further limitation to the generalization of these results is that spectral moment measures were likely affected by the presence of the palatometer pseudopalate. Dean (2008) examined spectral characteristics of the /p, t, k, and ʃ/ consonants when spoken in sentences for this same corpus of data (Sanders, 2007). Spectral characteristics for these sounds were measured before the pseudopalate was placed in the participants' mouths, immediately after the pseudopalate was placed, and following 20 minutes of conversation with the pseudopalate in place. Dean reported that although some adaptation was observed after 20 minutes of conversation, there was still a significant disturbance of the spectral characteristics compared to the spectral characteristics observed without the pseudopalate in place.

Another serious limitation to the generalization of these results was the crudeness of the EPG indices designed for this study. It was difficult to design a measure that could quantify a two-dimensional shape into one number that would lend itself to correlation analysis. Future researchers will be able to improve on these indices to find a more accurate and sensitive way of describing and quantifying lingua-palatal contact patterns.

Another limitation was that the 20 ms spectral moments measures are averages of the results for every two Hamming windows because the window advance rate was twice that of the EPG data. Thus, results for 20 ms spectral moments and EPG correlations are not as precise as the results for 40 ms correlations.

Furthermore, a large number of correlations were computed for this study. No alpha adjustments were made to compensate for the increased risk of a Type-I error, and the reader is encouraged to consider the results in this light.

Conclusions and Suggestions for Future Research

Overall, the most promising finding from this study is that there are in some cases strong and highly significant correlations between changes in tongue contact patterns and spectral mean and variance, particularly where individual speakers are considered. However, because of the limitations inherent in this study, generalization of specific correlations would need to be undertaken with considerable caution. Future research must improve upon the EPG indices developed for this study and implement newer EPG software that more closely links the palatal contact data with the acoustic data. When these limitations are eliminated, future research could more confidently focus on the relationship between changes in fricative grooves and changes in spectral mean and variance and hopefully draw more solid conclusions than this initial study allowed.

References

Ball, B. J., & Code, C. (Eds.). (1997). *Instrumental clinical phonetics*. London, England: Whurr Publishers.

Borden, G. J., & Harris, K. S. (1984). *Speech science primer: Physiology, acoustics and perception of speech.* Baltimore: Williams & Wilkins.

Dean, K. L. (2008). *The effect of a pseudopalate on voiceless obstruent production: A spectral evaluation of adaptation,* Unpublished master's thesis, Brigham Young University, Provo, Utah.

Farnetani, E., & Provaglio, A. (1991). Assessing variability of lingual consonants in Italian. *Quaderni del Centro di Studio per le Ricerche di Fonetica, 10,* 118–45.

Fletcher, S. G. (1992). *Articulation: A physiological approach.* Singular Publishing Group: San Diego.

Fletcher, S. G., McCutcheon, M. J., & Wolf, M. B. (1975). Dynamic palatometry. *Journal of Speech and Hearing Research*, *18*, 812-819.

Forrest, K., Weismer, G., Elbert, M., & Dinnsen, D. A. (1994). Spectral analysis of target-appropriate /t/ and /k/ produced by phonoligically disordered and normally articulating children. *Clinical Linguistics and Phonetics, 8,* 267-281.

Forrest, K., Weismer, G., Hodge, M., & Dinnsen, D. A. (1990). Statistical analysis of word-initial /k/ and /t/ produced by normal and phonologically disordered children. *Clinical Linguistics and Phonetics, 4,* 327-340.

Forster, C., & Hardcastle, W. (1998). An electropalatographic (EPG) study of the speech of two stuttering subjects. *International Journal of Language and Communication Disorders*, *33*, 358-363.

Fox, R. A., & Nissen, S. L. (2005). Sex-related acoustic changes in voiceless English fricatives. *Journal of Speech, Language and Hearing Research,* 4, 753-765.

Gibbon, F. E. (2004). Abnormal patterns of tongue-palate contact in the speech of individuals with cleft palate. *Clinical Linguistics and Phonetics, 18*(4-5), 285-311.

Hardcastle, W. J., Gibbon, F., & Nicolaidis, K. (1991). EPG data reduction methods and their implications for studies of lingual coarticulation. *Journal of Phonetics, 19*, 251-266.

Hardcastle, W. J., Gibbon, F., & Scobbie, J. M. (1995). Phonetic and phonological aspects of English affricate production in children with speech disorders. *Phonetica*, *52*, 242-250.

Hoole, P., Nguyen-Trong, N., & Hardcastle, W. (1993). A comparative investigation of coarticulation in fricatives: Electropalatographic, electromagnetic and acoustic data. *Language and Speech, 36*(2, 3), 235-260.

Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English Fricatives. *The Journal of the Acoustical Society of America, 108*, 1252-1263.

Kardach, J., Wincowski, R., Metz, D. E., Schiavetti, N., Whitehead, R. L., & Hillenbrand, J. (2002). Preservation of place and manner cues during simultaneous communication: a spectral moments perspective. *Journal of Communication Disorders, 35,* 533-542.

Kent, R. D., & Read, C. (2002). *Acoustic analysis of speech, 2nd Edition*. Albany, NY: Delmar.

Kydd, W. L., & Belt, D. A. (1964). Continuous palatography. *Journal of Speech and Hearing Disorders, 29,* 489-492.

LogoMetrix Palatometeric System [Computer software]. Tuscon, AZ: LogoMetrix Corporation.

MATLAB Version 6.1.0.450 (2001). The Language of Technical Computing [Computer Software]. Natick, MA: The MathWorks, Inc.

McAuliffe, M. J., Ward, E. C., & Murdoch, B. E. (2001). Tongue-to-palate contact patterns and variability of four English consonants in an /i/ vowel environment. *Logopedics, Phoniatrics, Vocology, 26,* 165-178.

McAuliffe, M. J., Ward, E. C., & Murdoch, B. E. (2006). Speech production in Parkinson's disease: I. An electropalatographic investigation of tongue-palate contact patterns. *Clinical Linguistics and Phonetics, 20*(1), 1-18.

Milenkovic, P. (2000). Time-frequency analysis for 32-bit windows [Computer software]. Retrieved September 9, 2004, from http://userpages.chorus.net/cspeech/

Murdoch, B. E., Goozée, J. V., Veidt, M., Scott, D. H., & Meyers, I. A. (2004). Introducing the pressure-sensing palatograph – the next frontier in electropalatography. *Clinical Linguistics and Phonetics, 18*(6-8), 433-445.

Nissen, S. L. (2003). *An acoustic analysis of voiceless obstruents produced by adults and typically developing children.* Unpublished doctoral dissertation, Ohio State University, Columbus.

Nissen, S. L., & Fox, R. A. (2005). Acoustic and spectral characteristics of young children's fricative productions: A developmental perspective. *The Journal of the Acoustical Society of America,* 4, 2570-2578.

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

O'Shaughnessy, D. (1987). *Speech communication human and machine.* Reading, Massachusetts: Addison-Wesley Publishing Company.

Sanders, M. C. (2007). *Inter- and intra-speaker variability: A palatometric study.* Unpublished master's thesis, Brigham Young University, Provo, Utah.

Searl, J. (2003). Comparison of transducers and intra-oral placement options for measuring lingua-palatal contact pressure during speech. *Journal of Speech, Language, and Hearing Research, 46*, 1444–1456.

SPSS Version 16 (2007). [Computer software]. Chicago, IL: SPSS, Inc.

Tabain, M. (2001). Variability in fricative production and spectra: Implications for the hyper- and hypo- and quantal theories of speech production. *Language and Speech, 44*(1), 57-94.

APPENDIX

Word List Used During Data Collection

/i/	/ɑ/	/u/
atee	atah	atoo
adee	adah	adoo
akee	akah	akoo
agee	agah	agoo
asee	asah	asoo
azee	azah	azoo
anee	anah	anoo
ajee	ajah	ajoo
achee	achah	achoo
ashee	ashah	ashoo
ashee (voiced)	ashah (voiced)	ashoo (voiced)
alee	alah	aloo
aree	arah	aroo
ayee	ayah	ayoo
eeng	ahng	oong