Effects of Palatal Expansion on Speech Production

Jason Milton Meinhardt
Marquette University

Recommended Citation
Meinhardt, Jason Milton, "Effects of Palatal Expansion on Speech Production" (2017). *Master's Theses (2009 -)*. 429.
http://epublications.marquette.edu/theses_open/429

EFFECTS OF PALATAL EXPANSION ON SPEECH PRODUCTION

By

Jason Milton Meinhardt, DDS

A Thesis submitted to the Faculty of the Graduate School,
Marquette University,
In Partial Fulfillment of the Requirements for
The Degree of Master of Science

Milwaukee, Wisconsin

August 2017

ABSTRACT
EFFECTS OF PALATAL EXPANSION ON SPEECH PRODUCTION

Jason Milton Meinhardt, DDS

Marquette University, 2017

Introduction: Rapid palatal expanders (RPEs) are a commonly used orthodontic adjunct for the treatment of posterior crossbites. RPEs are cemented to bilateral posterior teeth across the palate and thus may interfere with proper tongue movement and linguopalatal contact. The purpose of this study was to identify what specific role RPEs have on speech sound production for the child and early adolescent orthodontic patient.

Materials and Methods: RPEs were treatment planned for patients seeking orthodontics at Marquette University. Speech recordings were made using a phonetically balanced reading passage ("The Caterpillar") at 3 time points: 1) before RPE placement; 2) immediately after cementation; and 3) 10-14 days post appliance delivery. Measures of vocal tract resonance (formant center frequencies) were obtained for vowels and measures of noise distribution (spectral moments) were obtained for consonants. Two-way repeated measures (ANOVA) was used along with post-hoc tests for statistical analysis.

Results: For the vowel /i/, the first formant increased and the second formant decreased indicating a more inferior and posterior tongue position. For /e/, only the second formant decreased resulting in a more posterior tongue position. The formants did not return to baseline within the two-week study period. For the fricatives /s/, /ʃ/, /t/, and /k/, a significant shift from high to low frequencies indicated distortion upon appliance placement. Of these, only /t/ fully returned to baseline during the study period.

Conclusion: Numerous phonemes were distorted upon RPE placement which indicated altered speech sound production. For most phonemes, it takes longer than two weeks for speech to return to baseline, if at all. Clinically, the results of this study will help with pre-treatment and interdisciplinary counseling for orthodontic patients receiving palatal expanders.

ACKNOWLEDGEMENTS

Jason Milton Meinhardt, DDS

I would like to acknowledge my advisor, Dr. Jeffrey Berry, for all his help in advancing my knowledge of speech pathology and its applicability to orthodontics. I also would like to thank my committee, Drs. Dawei Liu and Bhoomika Ahuja, for their help along the way. Thank you to my family for the unconditional love and support over the years. A special thanks to my father, Dr. Carl Meinhardt, for sparking my interest in orthodontics in the first place. Finally, thank you to my grandfather, the deceased Dr. Milton Meinhardt, for your compassion to our profession and people in general continues to serve as a role model for me even today.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

As clinicians, it is important to be aware of any potential hardships arising from the use of our appliances in order to properly educate patients on what to expect. Often overlooked are the speech complications resulting from the use of an orthodontic expander. The Hyrax RPE design is banded to the bilateral maxillary first molars across the palate connecting to a central jackscrew mechanism. This relatively bulky appliance is used to widen the narrow maxillary arch and can interfere with the proper tongue to palate contact needed for normal speech sound production.

CHAPTER II

BACKGROUND AND SIGNIFICANCE

Anatomy

Over 100 muscles located throughout the chest, abdomen, neck, and head are carefully controlled to produce speech (Shriberg & Kent, 2003). Three main functional systems exist in creating speech production: respiratory, laryngeal, and supralaryngeal. Speech in its elementary form is created by variations in air pressure. This air originates in the lungs where air is expelled creating the pressure necessary to generate sound. Twelve to eighteen breaths per minute is considered normal for a resting individual (Skinner & Shelton, 1978). The air travels from the lungs to the larynx, or "voice box," located at the top of the trachea and composed of cartilage and muscles. Located inside the larynx are small muscles termed the vocal folds, which are the vibrating component used to produce sounds (Seikel, Drumright, & Seikel, 2004). For the adult male, they are approximately ¾" long, while for females and children they are shorter. The vocal folds vibrate about 125 times per second for an adult male, 250 times per second for an adult female, and 500 times per second for a crying newborn baby (Shriberg & Kent, 2003). These different rates of vocal fold vibration lead to perceived different pitches. This explains why a man's voice resonates lower in pitch than does a female's. Finally, the supralaryngeal system is composed of the pharyngeal, oral, and nasal cavities. Most of the sounds of the American English language are formed by modifying one of these three cavities. Air travels from the larynx to the supralaryngeal system and is acted on by one of the moving structures called articulators (Seikel et al., 2004).

There are numerous articulators but the most important of these is the tongue located at the floor of the oral cavity. The two main groups of muscles making up the tongue are the intrinsic muscles involved in changing the shape of the tongue, and the extrinsic muscles which allow movement of the tongue in the oral cavity (Skinner & Shelton, 1978). There are four main areas of the tongue: tip, blade, dorsum, and root. The tongue tip (apex) at rest is the most anterior part of the tongue. It is involved in over 50% of consonant contacts spoken in English. The tongue blade is just posterior to the tip and seldom used for constriction and shaping the tongue. The dorsum (back) is a large segment that contacts the hard and soft palate during articulation. Lastly, the root of the tongue is involved in shaping the vocal tract as it extends from the dorsum to the front wall of the pharynx (Seikel et al., 2004).

Consonants

American English speech sounds can be classified into two main categories: consonants and vowels. Consonants are differentiated from vowels based on the degree of airway constriction caused by the articulators. This leads to far more defects in articulation for consonants than vowels (Bloodstein, 1984). According to Bloodstein (1984), consonant articulation is categorized in three basic dimensions: place, manner, and voice. The place of articulation in the vocal tract can be further divided into bilabial, labiodental, linguadental, lingual-alveolar, linguopalatal, linguavelar, and glottal sounds. We will primarily focus on bilabial consonants (approximation of the two lips), labiodental sounds (lower lip contacting the upper teeth), lingua-alveolar sounds (tip of tongue located at alveolar ridge), linguopalatals (front of tongue contacting the hard palate), and linguavelar sounds (elevating back of tongue to velum).

Next, the manner in which consonants are formed can be categorized into various groups: stop-plosives, fricatives, nasals, glides, semivowels, and affricatives. Stop-plosives are produced by an occlusion of the airflow followed by a sudden release of the air pressure between the articulators producing a burst. Stops account for approximately one-third of all consonants produced by adults and thus account for a major part of all English words (Mines, Hanson, & Shoup, 1978). The other manner category of consonants, fricatives, are created by articulator constriction thus leading to air flow through the oral cavity that is turbulent producing a continuous friction noise (Bloodstein, 1984).

The last dimension of consonants is voicing which can be further subdivided into voiced and voiceless sounds. Cognate pairs share the same place of articulation and manner but differ based on their voicing. For example, the alveolar fricative /z/ as in "*zip*" is considered voiced meaning the vocal folds vibrate, while another alveolar fricative /s/ as in "*sip*" is voiceless (Shriberg & Kent, 2003). The six consonant sounds selected for analysis in this study are summarized in Table 1 (Bloodstein, 1984). Note that all six consonant sounds are voiceless.

	Position of Articulation				
Manner of Articulation	Bilabial	Labiodental	Lingua-alveolar	Linguopalatal	Linguavelar
Stop-plosives	/p/ - pen		/t/ - top		/k/ - call
Fricatives		/f/ - fill	/s/ - sun	/ʃ/ - she	

Table 1 - Categorization of American English consonant sounds

Vowels

A vowel is defined as "a voiced sound in forming which the air issues in a continuous stream through the pharynx and mouth, there being no obstruction and no narrowing such as would cause audible friction" (Roach, 2004, p. 73-74). Vowels are formed by vocal tones that are modified in the oral cavity by changes in tongue position (Travis, 1957). The listeners' perception of a particular vowel is determined by the position of the major constriction of the tongue (front, center, or back), the degree of constriction (high, middle, or low), and lip rounding (Skinner & Shelton, 1978).

As described by Shriberg & Kent (2003), the vertical position of the tongue, high-low (superior-inferior) is termed tongue height. High vowels are produced with the tongue superior towards the roof of the oral cavity while low vowels are produced with the tongue depressed towards the oral cavity floor. All the intermediate tongue positions can be described accordingly (e.g. high-mid, mid, mid-low). The horizontal position of the tongue, front-back (anterior-posterior), is termed tongue advancement. As the terms imply front vowels are articulated with the tongue in the most anterior position while the back vowels are formed with the tongue in a retruded position. Any intermediately formed vowels in the sagittal plane are termed central. The 6 vowels analyzed in this study are summarized in Table 2 (Skinner & Shelton, 1978). However, it is important to note that there is individual variability in the range of formation of these vowel phonemes. The range of these vowels blends by fine degrees and overlap can be observed pending different speakers and dialectal differences (Bloodstein, 1984).

	Tongue Advancement	
Tongue Height	Front	Back
High	/i/ - *e*at	/u/ - s*u*it
Mid	/e/- v*a*cation	/o/ - *o*bey
Low	/æ/ - *a*t	/ɑ/ - f*a*ther

Table 2 - Categorization of American English vowel sounds

Although the position of the tongue is primarily involved in distinguishing vowels, lip configuration must be briefly discussed for completion. Lip configuration can be described as rounding, protrusion, retraction, spreading, eversion, and narrowing. Lip rounding, or lips in the pursed and protruded manner, lengthens the vocal tract which can alter the acoustics of vowel sounds. In the English language, this is primarily utilized in the formation of posterior vowels (Shriberg & Kent, 2003).

Unlike consonants, all vowels are voiced and are produced in the same manner. The phonetic differences are observed because of the unique vocal tract shape and the changing tongue posture (Skinner & Shelton, 1978). No turbulent air is observed during vowel production. The six vowels noted in Table 2 are considered pure English vowels.

Speech Acoustics

The source-filter model, as described by Kent & Kim (2008), describes a source of sound energy that is acted upon by a filter. The energy source produced by the vibrating laryngeal vocal folds is filtered by passing through the vocal tract. The vocal tract is made up of the pharynx, nasal cavity, and the oral cavity which houses the main articulators. The main energy sources can be summarized into four categories: quasi-periodic glottal pulses, turbulence noise, noise burst, and silence. These different sources correspond to various locations in the vocal tract during speech sound production. Quasi-periodic glottal pulses are associated with voiced vowels as vibration of the vocal folds is produced. Turbulent noise and noise burst are associated with fricatives and stop consonants, respectively. Filtering of the sound energy occurs by the vocal tract resonances. Voiced vowels are filtered by the supralaryngeal cavities whereas fricatives are modified by the cavities on either side of the constriction.

While voiceless fricatives are created by modifying a turbulent noise source, vowels have distinct acoustic frequency bands called formants. Looking at a spectrogram, these formants appear as distinct dark horizontal delineated bands of sound energy (see Figure 1). The center frequencies of these formants are typically used to discretely characterize a vowel acoustically. Three prominent frequency formants are considered most important to understand. The lowest frequency band, F1, is related to the tongue height when producing a specific vowel. When graphed in a standard F1/F2 plot, decreasing F1 values (moving upward along the y-axis) correspond with increases in the height of the tongue. F2 is related to the anterior-posterior tongue advancement. Increasing F2 values on the x-axis correspond with more anterior positions of the primary tongue-to-palate constriction. F3 values are important in rhotic sounds but need not be discussed for the purpose of this study. The exact formant frequencies differ across speakers due to differences in anatomical vocal tract size. Yet the relative locations of formant frequencies for a particular vowel typically maintain across speakers which allows for analysis (Nell, 2010).

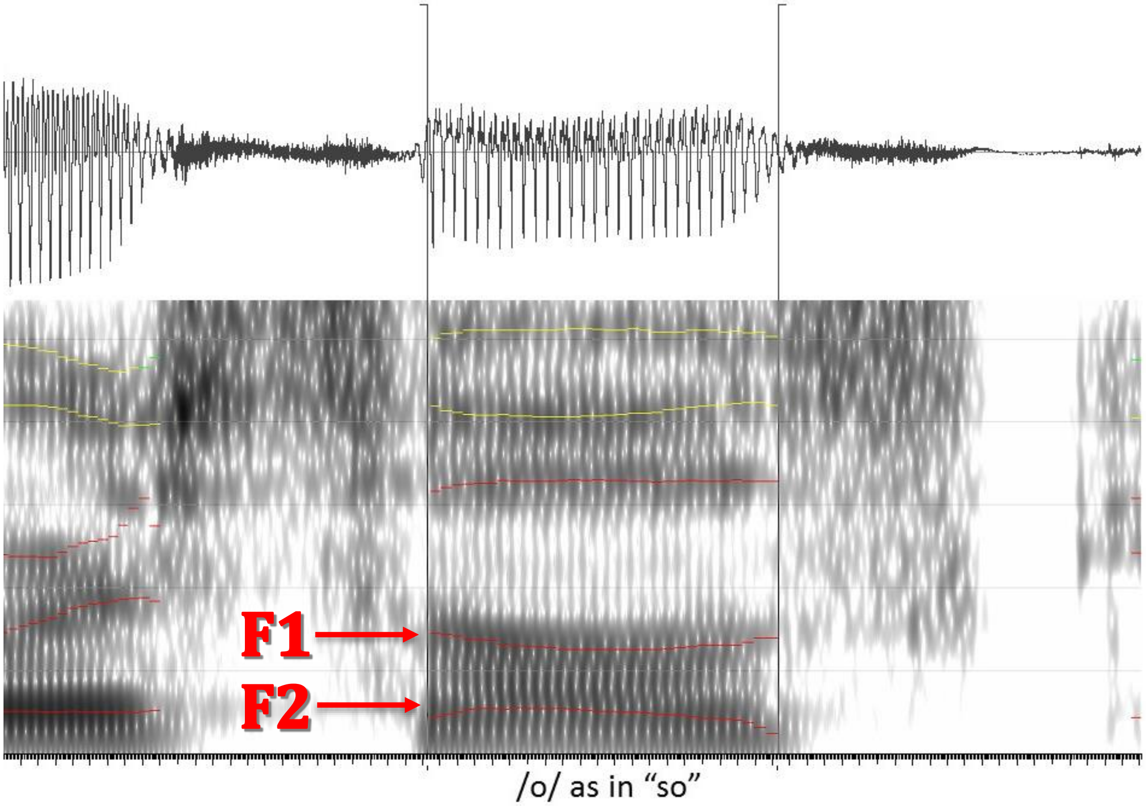


Figure 1 – 3D graphical display of sound "so" with time on the X-axis, frequency on the Y-axis, and intensity represented as changes in darkness-lightness

Acoustic Analysis

In order to observe the continuously changing acoustic elements of speech, an electronic recording can be made and a speech spectrogram can be utilized. Frequency in Hertz is plotted on the vertical (Y) axis and time in seconds is on the horizontal (X) axis (Skinner & Shelton, 1978). Acoustic analysis is a powerful tool used to describe disordered speech production in a quantitative manner (Shriberg & Kent, 2003). From the spectrogram, statistical moments can be measured and analyzed giving meaningful objective data: mean, variance, skewness, and kurtosis of the sound frequency-intensity distribution during a specified temporal region (Forrest, Weismer, Milenkovic, & Dougall, 1988).

Spectral moment analysis (SMA) is useful for quantifying and distinguishing between speech signals. It has been shown that SMA is useful in objectively distinguishing between the stop-plosive and fricative consonant groups (Forrest et al., 1988). Using SMA for fricative consonants is particularly useful for two reasons: it provides quantitative data that can be used to show clinically relevant speech changes, and it can distinguish between consonant sounds that may be unperceivable to the human ear alone (Mandulak, 2011).

Vowel formants are determined by their resonance patterns and appear as a dark band on the spectrogram. This black band represents the amount of energy that is present at a certain frequency. Each vowel has a specific pattern of formants in which its structure is determined by the length and the shape of the particular vocal tract. Typically, only the lowest two formant center frequencies, F1 and F2, are needed to identify the vowel on a spectrogram (Shriberg & Kent, 2003). During speech-acoustic analysis these can be obtained using a linear predictive coding (LPC) algorithm. This assumes a simple model of vocal tracts and separates acoustic features of vocal fold vibration from the filtering effects of the resonating, supraglottal cavities in order to estimate the formant center frequencies (Milenkovic, 2005).

History of Rapid Palatal Expanders

Rapid maxillary expansion (RME) is commonly used in young, growing patients who present with a posterior crossbite. The transverse discrepancy can be skeletal (narrow maxillary base or a wide mandible), dental, or a combination of the two (Bishara & Staley, 1987). In 1860, Emerson C. Angell was among the first to report on the procedure. He described a 14-year-old girl in which a jackscrew spanned the palate and was anchored to the first and second bicuspids to correct a maxillary transverse deficiency (Angell, 1860).

Since then numerous studies have been performed aiming to describe the process of maxillary expansion. It is now being advocated to correct posterior crossbites to redirect developing teeth into normal occlusion, eliminate any functional complications upon closing, to make beneficial dentoskeletal changes in a growing individual to reduce future treatment complexity (Bell, 1982), and to reduce the possibility of skeletal mandibular asymmetry (Kilic, Kiki, & Oktay, 2008). Andrew Haas, inventor of the Haas expander, describes the principal objective of palatal expansion as coordinating the maxillary and mandibular denture bases. This is obtained by utilizing a jackscrew delivering orthopedic force to the dental anchorage units ultimately maximizing the force on the palatal suture (Haas, 1970).

Appliance Design

The three main types of fixed palatal expanders containing jackscrews are the Haas, Hyrax, and bonded types. Hyrax and Haas expanders are secured by bands around the upper first molars and often the first premolars. The bonded expander requires no bands and is secured with cement over the occlusal surfaces of the posterior teeth. Regardless of expander type, a central jackscrew stretches across the palate, is soldered to the bands, and is activated at home. The Haas expander is similar to the Hyrax design but also includes acrylic covering the palate. Advocates of the tissue-borne Haas expander site a more parallel expansion force distributed to the teeth and alveolar processes (Haas, 1970). The Hyrax expander is more hygienic than the Haas as it is an all wire frame and causes the least irritation to the palatal mucosa (Bishara & Staley, 1987).

Other expanders come in the form of a removable plate with a central jackscrew or heavy spring, or a lingual arch such as a quad helix or W-arch (Profitt, Fields, & Sarver, 2013). The quad helix has been shown to be the least effective orthopedic device when directly compared to the Haas expander, Minne expander, Hyrax expander, and a removable expander. It was also reported that removable expanders were displaced before delivering adequate force to cause palatal suture separation (Chaconas & Caputo, 1982).

Effect of Age

Treatment intervention timing is critical when considering a palatal expander as growth ceases at different times in the three planes of space. Palatal expansion is more urgent in the early years as the transverse dimension is the first to cease. This is observed as the midpalatal suture becomes more tortuous and interdigitated with increasing age. Prior to pubertal growth, any expansion device will have a high success separating the midpalatal suture; however, by adolescence a heavier force directed from a jackscrew is more effective (Profitt et al., 2013).

A cadaver study performed by Persson and Thilander (1977) found that 5% of the suture was obliterated by age 25, however, large variability of ossification was noted. The earliest complete suture obliteration was observed in a 15-year-old female, while the oldest person without any suture union was a 27-year-old female, again showing great variability (Persson & Thilander, 1977). To summarize, the optimal upper age for expansion is 13-15 years of age; however, expansion may be possible in older patients but at a less predictable level (Bishara & Staley, 1987).

Articulation

One of the main disadvantages of an expander incorporating a jackscrew is its bulkiness in the palatal area (Profitt et al., 2013). This can lead to temporary speech difficulties as approximately 90% of all consonants are articulated in the anterior portion of the oral cavity (Leavy, Cisneros, & LeBlanc, 2016). This is especially important as there is less flexibility in producing consonant sounds as opposed to vowels as consonants require a more accurate positioning of the tongue (McFarland & Baum, 1995).

Lubit studied individuals with high or narrow palates and concluded that they more commonly have articulatory disorders (Lubit, 1967). Furthering Lubit's study, Laine concluded the /s/ sound was distorted at a higher rate in subjects with a narrower palate in all segments. One explanation for this distortion is less available space for the tongue movements required for appropriate articulation. Laine also found that medio-alveolar consonants are somewhat affected by the size of the maxillary arch but not the mandibular arch (Laine, 1986). Furthermore, no significant speech association was found between speech errors and molar classification, overjet, overbite, anterior crossbite, spacing, or crowding in a sample of 115 untreated individuals (Leavy et al., 2016).

Current State of the Problem

To date very few studies have looked at speech production and its relationship to palatal expanders. The first article by De Felippe, Da Silveira, Viana, & Smith (2010) involved a retrospective questionnaire given to 165 patients who received various designs of fixed rapid palatal expanders. Approximately 89% of patients believed that the expander affected their speech; however, it was impossible to determine what phonetic sounds and to what degree the speech was impaired. Most patients self-reported their speech returned to normal after one week.

Another more clinically based study by Stevens, Bressmann, Gong, & Tompson (2011), described the speech alterations of 22 patients that received Hyrax or bonded type expanders. Speech acceptability was rated by 10 naïve undergraduate students as well as an acoustic analysis performed for fricatives /s/, /ʃ/, and /i/ vowel sounds. It was determined that all three sounds were affected to some extent in speech sound production.

The purpose of this current study was to look at more broad range of consonants /f/, /s/, /ʃ/, /p/, /t/, and /k/, as well as a more inclusive list of vowel sounds /i/, /e/, /æ/, /u/, /o/, and /ɑ/ to better understand the effects of RPEs on speech sound production. Clinically, this information can be shared with the patient undergoing orthodontic treatment during initial pre-treatment counseling.

Assuming that tongue height is the primary factor related to the expander interference we might expect to see consonants and high voiced vowels being the most affected, followed by mid-high vowels, and finally low-mid vowels being the least affected during the placement of an RPE.

CHAPTER III

MATERIALS AND METHODS

Institutional research board approval was granted from Marquette University in Milwaukee, Wisconsin. All incoming Marquette Dental School Graduate Orthodontic patients were treatment planned with faculty and residents as normal; however, those between the ages of 8-15 and in need of a Hyrax expander were asked to take part in this study. The study did not alter the orthodontic treatment plan and did not add any additional treatment visits. Informed consent and specific study details were presented both written and verbally by the principal investigator (PI). Separate forms for the adult and child were presented and signatures of those willing to participate were obtained.

The participant pool included 15 talkers, comprised of 5 males (33%) and 10 females (66%). Ages ranged from 8-15 with a mean age of 11.3 years. Eight years was selected as the lower age limit as speech is developmentally considered to be at the mature adult motor and functioning stage at this age (Costello & Holland, 1986). Fifteen years was selected for the upper bound as it signifies the optimal age limit for true orthopedic expansion in the average patient (Bishara & Staley, 1987). Exclusion criteria consisted of patients unable to perform the reading and those with previous palatal expander experience.

All the orthodontic clinical work was completed by one of the graduate orthodontic residents assigned to the particular case. This includes separator placement, banding, impressions, and delivery of the Hyrax appliance. No lingual appliances were present during the study period as they have been shown to increase speech difficulty (Chen, Wan, & You, 2017). All 15 of the Hyrax expanders were made by the same certified dental technician, a full-time faculty member part of the graduate orthodontic program. All expanders included a central jackscrew and were attached to the maxillary first molar bands and occasionally also the first premolars, at the supervising faculty's discretion. All expanders were designed with the same lab protocol to ensure equal distance from the palate.

Speech recordings were made using a phonetically balanced reading passage, "The Caterpillar" (Patel et al., 2013), at three time points: 1) before RPE placement; 2) immediately after cementation; and 3) 10-14 days post appliance delivery. Speech recordings were captured using a small-diaphragm cardioid condenser microphone (AKG C1000 S MK4). Audacity® (http://audacity.sourceforge.net/) audio capturing software was used and recordings were saved on a password protected desktop computer in WAV format. The data was recorded with 16-bit encoding, 44.1 kHz sampling rate, and in a single monolithic channel. The recordings were captured in a quiet room with a 6-8" distance from the microphone to the corner of the subjects' mouth. All recordings were made by the PI.

Sound spectrograms (sonograms) are 3D patterns that visually represent time (horizontal axis), frequency or pitch perception (vertical axis), and intensity shown as degree of blackness (Shriberg & Kent, 2003). Measures of vocal tract resonance (formant center frequencies) were obtained for vowels and measures of noise distribution (spectral moments) were obtained for consonants using the TF32 spectrographic analysis software (Milenkovic, 2005). The temporal boundaries of

12 phonemes (49 total occurrences) were manually demarcated for each of the three passage readings recorded from the 15 patients using a wide-band spectrographic display. All spectrograms were analyzed with a 450 Hz bandwidth. See Appendix A for examples of the 12 phonemes manually demarcated for a 15-year-old female at T1.

As described by Shriberg & Kent (2003), a wide-band spectrographic display is utilized when identifying formants and acoustic changes during a short period of time. Formant center frequencies for the two most prominent vowel resonances (F1 & F2 in Hertz) were measured using a linear predictive coding algorithm and spectral distributions were obtained for unvoiced consonants (Milenkovic, 2005). Current analyses focus on speaker and time effects on the production of 6 different vowels.

CHAPTER IV

RESULTS

The statistical analyses were conducted by using a two-way repeated measures (ANOVA) to compare phoneme identity and time. Two dependent variables were analyzed for vowels: 1st formant center frequency (F1) and 2nd formant center frequency (F2). For consonants, the two dependent variables were: 1st spectral moment (S1) and 2nd spectral moment (S2). Post-hoc tests were also used to determine all pairwise comparisons between the Hyrax appliance for each of the phonemes. Due to the number of post-hoc tests run, a Bonferroni correction was done to avoid Type I error. This required a p-value of less than 0.00833 for statistical significance instead of 0.05.

Two vowels were altered by the palatal expander: /i/ and /e/. Both formant 1 and formant 2 were significant for /i/, while only formant 2 was significant for /e/. For /i/, F1 increased from baseline between T1-T2 (325 Hz to 353 Hz), and F2 decreased from T1-T2 (1956 Hz to 1773 Hz) but no other significant changes were noted. For /e/, F2 decreased from T1-T2 (1981 Hz to 1801 Hz). Complete data are detailed in Table 3 with the red bolded text indicating those vowels deemed statistically significant.

Formant frequencies differ across speakers due to differences in vocal tract size. Yet the relative locations of formant frequencies for a particular vowel typically maintain across speakers. Vowel normalization techniques transform formant frequency values to a speaker-general range and allow direct comparisons between different speakers and data pooling across speakers and within time conditions, which is critical to the current study. Lobanov's method of normalization was selected as it factors out anatomical and physiological differences in formant values while retaining sociolinguistic differences (Lobanov, 1971). F1-F2 formant plots at T1 showing normalized vowels for the 15 study participants are included in Appendix B.

Four consonants were altered by the palatal expander: /s/, /ʃ/, /t/, /k/. All the statistically significant data were associated with spectral moment 1 which represents the mean. Spectral moment 2, which represents the variance of the noise distribution, showed no statistical significance in this study. For /s/, /ʃ/, and /k/, the S1 frequency for T1 was significantly higher than that of T2's (7599 Hz to 6729 Hz, 5157 Hz to 4495 Hz, and 5176 Hz to 3913 Hz, respectively). For /t/, the S1 frequency for T2 was significantly lower than T1 and T3 (T1 = 7077 Hz, T2 = 6136 Hz, T3 = 6944 Hz). A full report of the data can be found in Table 4.

		i	**e**	**æ**	**u**	**o**	**ɑ**
T1	F1	**325**	**374**	592	347	432	626
	F2	**1956**	1981	1593	1359	1151	1393
T2	F1	**353**	**379**	594	344	420	623
	F2	**1773**	1801	1551	1308	1144	1367
T3	F1	**345**	**387**	608	352	419	632
	F2	**1838**	1889	1575	1356	1110	1364

Table 4: Frequency in Hertz for vowels across speakers

		f	**s**	**ʃ**	**p**	**t**	**k**
T1	S1	8100	**7599**	**5157**	3731	**7077**	**5176**
	S2	3558	2528	2098	2916	2535	2941
T2	S1	7547	**6729**	**4495**	3721	**6136**	**3913**
	S2	3625	2685	2137	3068	2670	2832
T3	S1	8049	**7228**	**5324**	3687	**6944**	**4279**
	S2	3671	2487	2119	3000	2504	2914

Table 5: Frequency in Hertz for consonants across speakers

CHAPTER V

DISCUSSION

A traditional experimental control group was not utilized in this study as comparing one speaker to another for a reference point does not yield valuable information due to interspeaker differences (see “normalized” vowel plots in Appendix A). Furthermore, no significant developmental changes in speech would be expected to occur in a 10-14 day period from T1-T3. Consequently, a repeated measures design was used.

Previous studies have utilized perceptual analysis to rank the degree of speaker impairment on a scale. There are several problems with auditory judgements: the assumption that listeners utilize similar perceptual labels, are calibrated to the same scale values, can isolate one perceptual dimension from numerous occurring, uniform reliability when judging, and can discern at a level accurate enough to make judgements smaller than interjudge differences needed for clinical classification (Kent, 1996). Perceptual inaccuracy has been demonstrated when listener’s fail to recognize when a non-speech sound, such as a cough, has been substituted for a speech sound (Warren, 1976). Furthermore, judges may fail to agree with one another when rating voices; “the differences between clinicians were large enough to suggest that averaging data across subjects may produce misleading results and obscure important aspects of an individual subject’s perceptual behavior” (Kreiman, Gerratt, & Precoda, 1990, p. 109). It has also been shown that the judgement of misarticulation is not created equal for all speech sounds. It appears that judgements are more accurate for /s/ sounds than for /r/ sounds (Elbert, Shelton, & Arndt, 1967). While this is not meant to be an exhaustive summary, it should be noted that there are reliability issues when solely utilizing a perceptual analysis method. An acoustic approach to data analysis allowed for a more objective appraisal of the phoneme-specific effects of the palatal expander.

Our present study has shown that Hyrax rapid palatal expanders influenced two of the six vowels and four of the six consonants analyzed. When the appliance was placed immediately prior to the T2 point, the patients' speech noticeably deteriorated perceptually. Of the six affected phonemes, only /t/ showed adaptation back to baseline at T3 (10-14 days after insertion of the RPE).

The two affected vowels, /i/ and /e/, both showed a decrease for F2 from T1-T2, and /i/ also had a significant increase in F1 from T1-T2. For both frequency bands and vowel phonemes, a decrease in frequency from T2-T3 was noted; however, this decrease was not found to be statistically significant. This suggests that talkers may have learned to compensate somewhat for the RPE by adapting tongue position, but a full return to baseline was not noted within the two-week period, suggesting that they could not produce these phonemes using the baseline tongue positions. Increasing values for F1 correspond with more inferior tongue positioning, while decreasing values for F2 indicate more posterior positioning of the tongue. Thus, while trying to adapt to the orthodontic appliance, the tongue was positioned more inferior and posterior for /i/, and more posterior for /e/ when forming vowel sounds. These findings for /i/ are consistent with past literature in that F1 increased and F2 decreased; however, it took 2-3 months for F1 to return to baseline and 6-8 months for F2 (Stevens et al., 2011). It is no surprise that that most affected vowel, /i/, is formed in the most anterior and superior aspect of the oral cavity and /e/ is formed anterior and in the mid height range.

The affected consonants out of the six selected for analysis are: /s/, /ʃ/, /t/, and /k/. Only spectral moment 1 (mean) was found to be significant while spectral moment 2 (variance of noise distribution) was not found to be significant for any of the consonants. All four affected consonants decreased in frequency for S1, roughly indicating a more posterior articulation. For example, at T1, /s/ was at approximately 7600 Hz while /ʃ/ was at 5150 Hz; when switching from /s/ to /ʃ/ the tongue retracts in the oral cavity which increases the length of the resonating tube in front of the articulation and thus decreases the frequency. From T1-T2, all four previously mentioned consonants were statistically significant. For /s/ and /k/, the frequency increased from T2-3 for both but not to a statistically significant level; this suggests they adjusted and moved their tongue forward. Overall, T3 finished at a frequency higher than T2, but lower than T1 which suggests they didn't move their tongue all the way back to the original position. Phoneme /t/ at T2 was significantly lower than T1 and T3. It appears that for this sound the tongue adapted to the appliance in under 2 weeks. It has been shown that there is more flexibility for a perceptually appropriate /t/ than for a /s/ sound which requires relatively more accurate tongue positioning for its production (Flege et al., 1988). For /ʃ/, the S1 frequency decreased from T1-T2 but then increased from T2-T3 to a frequency higher than T1. This was not noted for any other consonant and indicates tongue over adaptation by dramatically changing how the sound was articulated, resulting in a totally different /ʃ/ sound. In the study by Stevens et al. (2011), they analyzed spectral moments for /s/ and /ʃ/ and likewise found significant distortions. It wasn't until 2-4 weeks post insertion that adaptation occurred at levels similar to baseline.

In a retrospective patient survey subject to RPE's, 89.4% claimed the expander affected their speech; however, no conclusions were drawn regarding which phonemes were affected (De Felippe et al., 2010). Previous studies utilizing an intraoral bite block and an artificial palate have shown that consonant production is more affected than vowels (McFarland & Baum, 1995; Baum & McFarland 2000). This present study has shown that for RPE's, persistent deviation from baseline speech was noted for both vowels and consonants, and of the six affected phonemes, only /t/ returned to baseline within 2 weeks.

CHAPTER VI

SUMMARY AND CONCLUSIONS

- Of the twelve phonemes analyzed, half (/i/, /e/, /s/, /ʃ/, /t/, and /k/) were statistically affected between T1-T2.
- Talkers learned to adjust tongue positions for the following phonemes between T2-T3 but did not fully return to baseline: /i/, /e/, /s/, /k/.
- The phoneme, /ʃ/, showed a dramatic change in how the tongue was positioned, showing a significantly more anterior articulation at T3 compared to baseline.
- The phoneme, /t/, is the only sound that participants learned to completely adjust tongue position back to baseline, despite the RPE.
- Clinically, these findings are important as more insight can be given to patient's pre-treatment that are treatment planned for Hyrax expanders. For those patients under the care of both an orthodontist and speech pathologist, interdisciplinary collaboration can now be more goal focused to help with tongue position changes for specific phonemes. It is also now clear that talkers do not learn to adjust tongue position for the RPE for all sounds within a 2-week period, which is typically about the time an orthodontist may do an expansion check.
- Future research may incorporate: inclusion of more phonemes, longer study length to include fixed appliance treatment and retention time points, and a

larger sample size to look across more factors such as age, gender, and native language.

REFERENCES

Angell, E. (1860). Treatment of irregularity of the permanent or adult teeth. *Dental Cosmos, 1*, 540-544.

Baum, S. R., & McFarland, D. H. (2000). Individual differences in speech adaptation to an artificial palate. *The Journal of the Acoustical Society of America, 107*(6), 3572-3575.

Bell, R. A. (1982). A review of maxillary expansion in relation to rate of expansion and patient's age. *American Journal of Orthodontics and Dentofacial Orthopedics, 81*(1), 32-37.

Bishara, S. E., & Staley, R. N. (1987). Maxillary expansion: Clinical implications. *American Journal of Orthodontics and Dentofacial Orthopedics, 91*(1), 3-14.

Bloodstein, O. (1984). *Speech pathology: An introduction* (Second ed.) Houghton Mifflin Company.

Chaconas, S. J., & Caputo, A. A. (1982). Observation of orthopedic force distribution produced by maxillary orthodontic appliances. *American Journal of Orthodontics, 82*(6), 492-501.

Chen, J., Wan, J., You, L. (2017). Speech and orthodontic appliances: a systematic literature review. *European Journal of Orthodontics,* 1-8.

Costello, J. M., & Holland, A. L. (1986). The phonological system: normal acquisition. *Handbook of Speech and Language Disorders* (pp. 25-74). San Diego, CA: College-Hill Press.

De Felippe, N. L., Da Silveira, A. C., Viana, G., & Smith, B. (2010). Influence of palatal expanders on oral comfort, speech, and mastication. *American Journal of Orthodontics and Dentofacial Orthopedics, 137*, 48-53.

Elbert, M., Shelton, R. L., & Arndt, W. B. (1967). Intensity perception. I. Preliminary theory of intensity resolution. *Journal of the Acoustical Society of America, 46*, 372-383.

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

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

Haas, A. J. (1970). Palatal expansion: Just the beginning of dentofacial orthopedics. *American Journal of Orthodontics, 57*(3), 219-255.

Kent, R. D. (1996). Hearing and Believing: Some Limits to the Auditory-Perceptual Assessment of Speech and Voice Disorders. *American Journal of Speech-Language Pathology, 5*(3), 7-23.

Kent, R. D., & Kim, Y. (2008). Acoustic Analysis of Speech. *The Handbook of Clinical Linguistics* (pp. 360-380). Blackwell Publishing.

Kilic, N., Kiki, A., & Oktay, H. (2008). Condylar asymmetry in unilateral posterior crossbite patients. *American Journal of Orthodontics and Dentofacial Orthopedics, 133*(3), 382-387.

Kreiman, J., Gerratt, B. R., & Precoda, K. (1990). Listener experience and perception of voice quality. *Journal of Speech and Hearing Research, 33*, 103-115.

Laine, T. (1986). Articulatory disorders in speech as related to size of the alveolar arches. *European Journal of Orthodontics, 8*(3), 192-197.

Leavy, K. M., Cisneros, G. J., & LeBlanc, E. M. (2016). Malocclusion and its relationship to speech sound production: Redefining the effect of malocclusal traits on sound production. *American Journal of Orthodontics and Dentofacial Orthopedics, 150*(1), 116-123.

Lobanov, B. M. (1971). Classification of Russian vowels spoken by different speakers. *The Journal of the Acoustical Society of America*, *49*, 606-608.

Lubit, E. C. (1967). The relationship of malocclusion and faulty speech articulation. *Journal of Oral Medicine, 22*(2), 47-55.

Mandulak, K. C. (2011). "I can see what you're saying": Clinical utility of spectral moment analysis. *Perspectives on Speech Science and Orofacial Disorders, 21*, 44-54.

McFarland, D. H., & Baum, S. R. (1995). Incomplete compensation to articulatory perturbation. *The Journal of the Acoustical Society of America, 97*(3), 1865-1873.

Milenkovic, P. (2005). TF32-Computer Program (Madison, WI).

Mines, M., Hanson, B., & Shoup, J. (1978). Frequency of occurrence of phonemes in conversational English. *Language and Speech, 21*(3), 221-241.

Nell, A. T. (2010). Using acoustic phonetics in clinical practice. *Perspectives on Speech Science and Orofacial Disorders, 20*, 14-24.

Patel, R., Connaghan, K., Franco, D., Edsall, E., Forgit, D., Olsen, L., Ramage, L., Tyler, E., Russell, S. (2013). "The Caterpillar": A Novel Reading Passage for Assessment of Motor Speech Disorders. *American Journal of Speech-Language Pathology, 22* 1-9.

Persson, M., & Thilander, B. (1977). Palatal suture closure in man from 15 to 35 years of age. *American Journal of Orthodontics, 72*(1), 42-52.

Profitt, W. R., Fields, H., & Sarver, D. M. (2013). *Contemporary orthodontics* (Fifth ed.). St. Louis, Missouri: Elsevier.

Roach, P. (2004). *Phonetics* (Third ed., pp. 73-74) Oxford University Press.

Seikel, J. A., Drumright, D., & Seikel, P. (2004). *Essentials of anatomy & physiology for communication disorders* Thomson Delmar Learning.

Shriberg, L. D., & Kent, R. D. (2003). *Clinical phonetics* (Third ed.) Pearson Education, Inc.

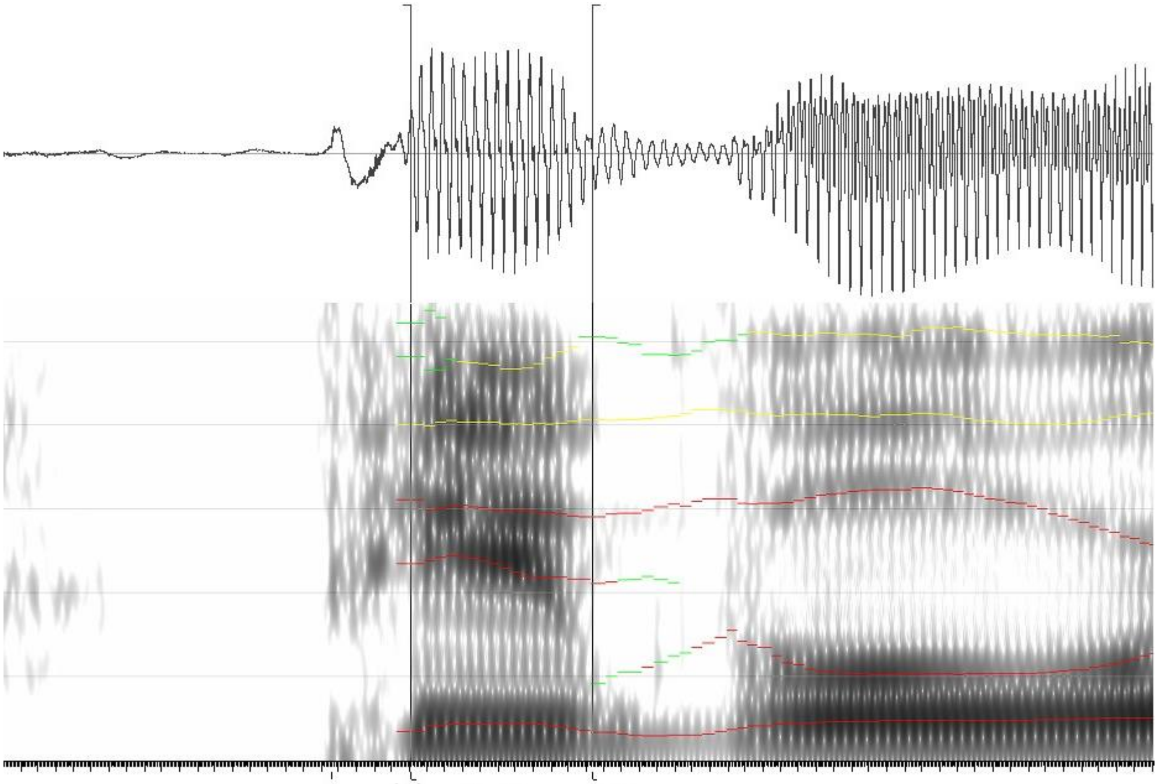
Skinner, P. H., & Shelton, R. L. (1978). *Speech, language and hearing normal processes and disorders* (Second ed.) John Wiley & Sons, Inc.

Stevens, K., Bressmann, T., Gong, S. G., & Tompson, B. D. (2011). Impact of a rapid palatal expander on speech articulation. *American Journal of Orthodontics and Dentofacial Orthopedics, 140*(2), e67-75.

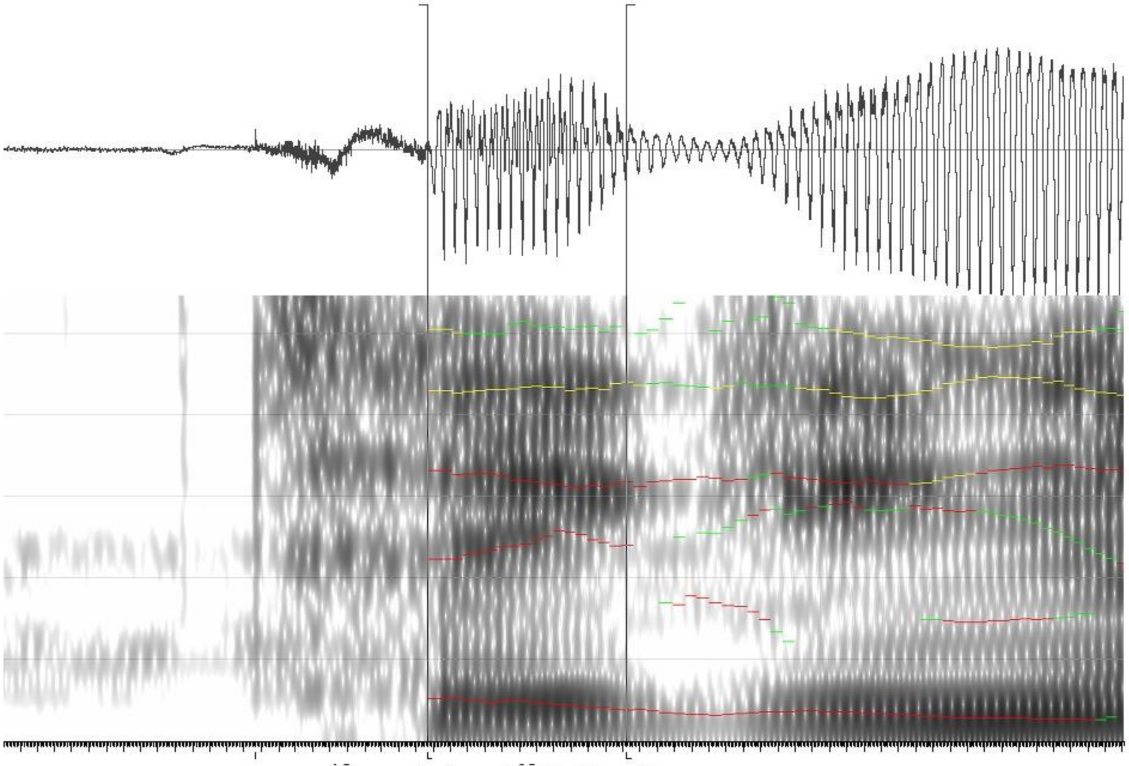
Travis, E. L. (1957). *Handbook of speech pathology*. New York: Appleton Century Crofts, Inc.

Warren, R. (1976). Auditory illusions and perceptual processes. In N. J. Lass (Ed.), *Contemporary issues in experimental phonetics* (pp. 389-418). New York: Academic Press.

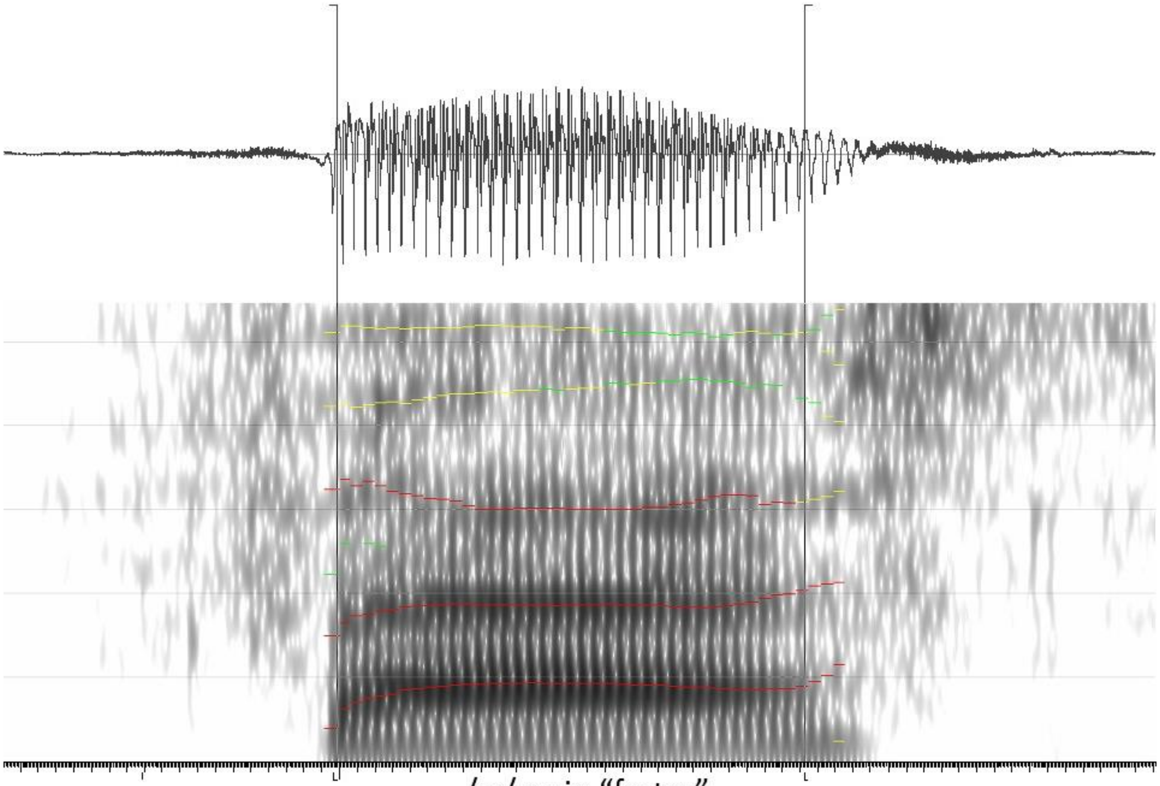
APPENDIX A



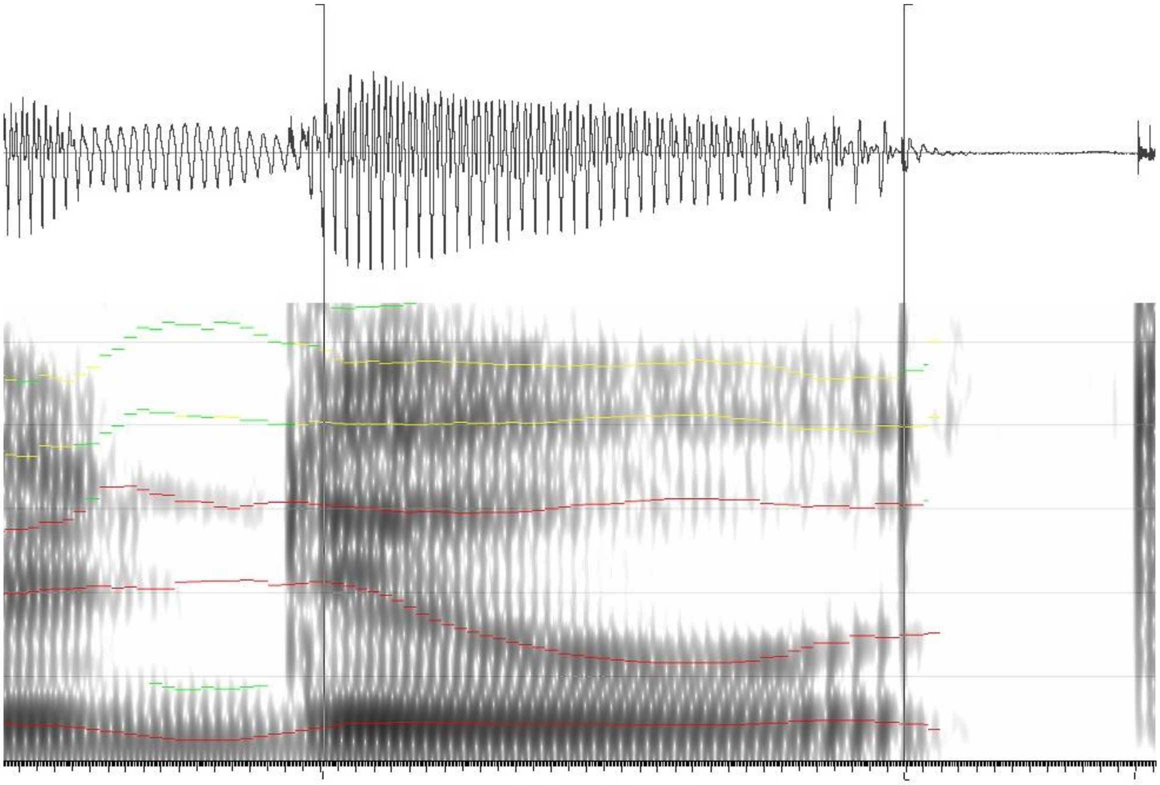
/i/ as in “people”



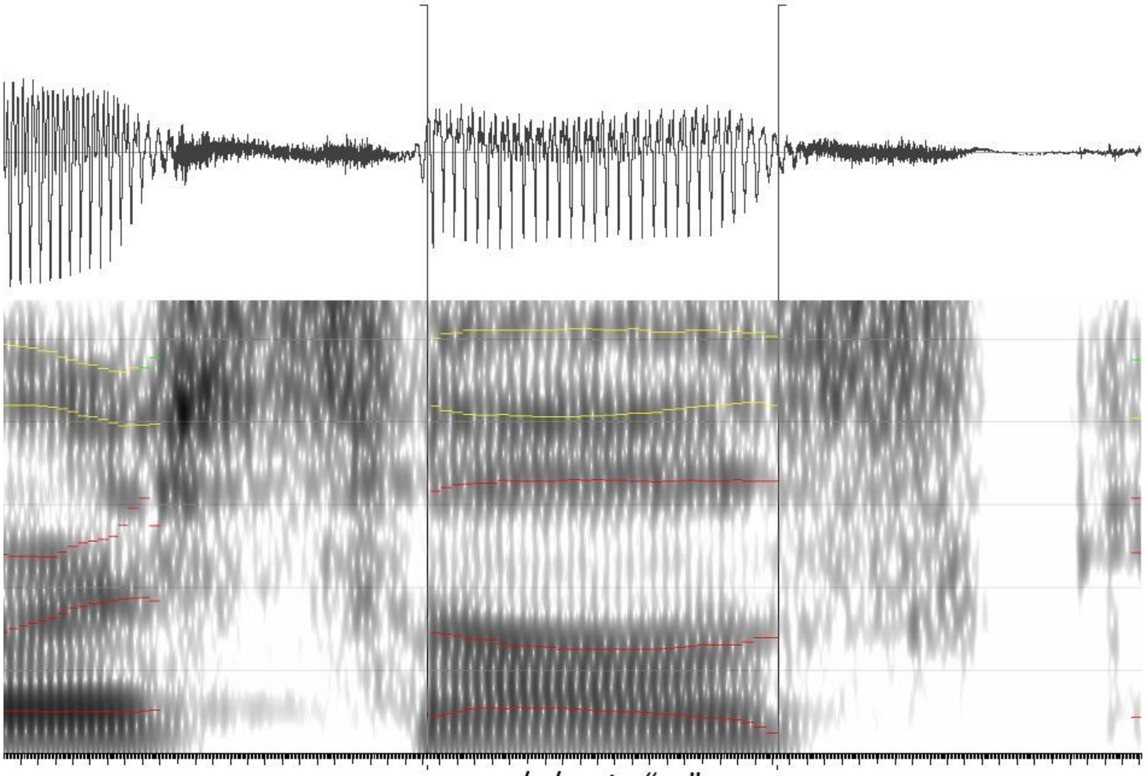
/e/ as in “taking”



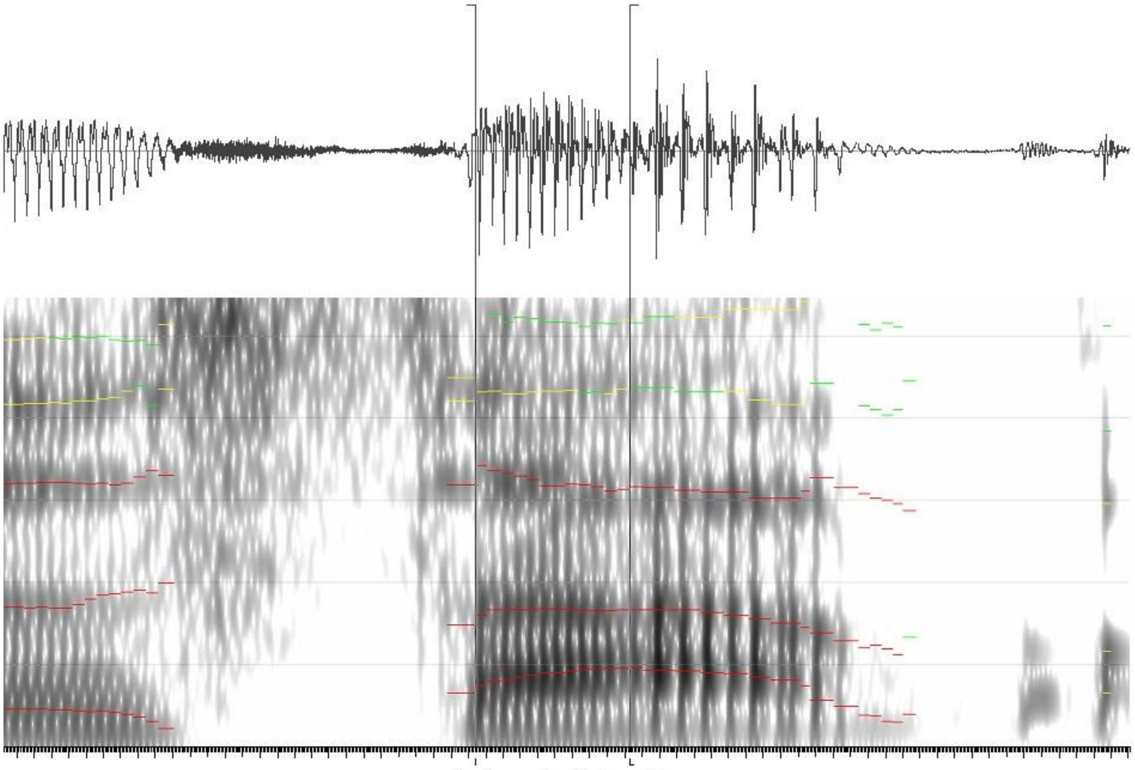
/æ/ as in “faster”



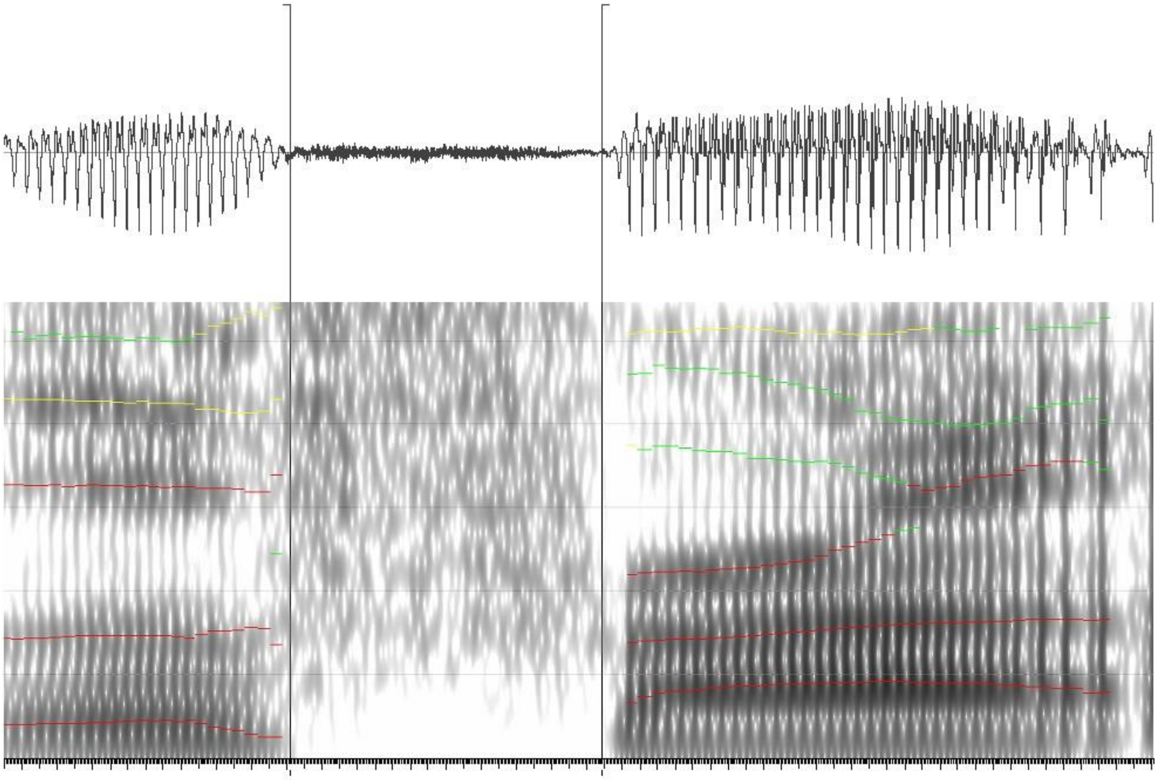
/u/ as in “do”



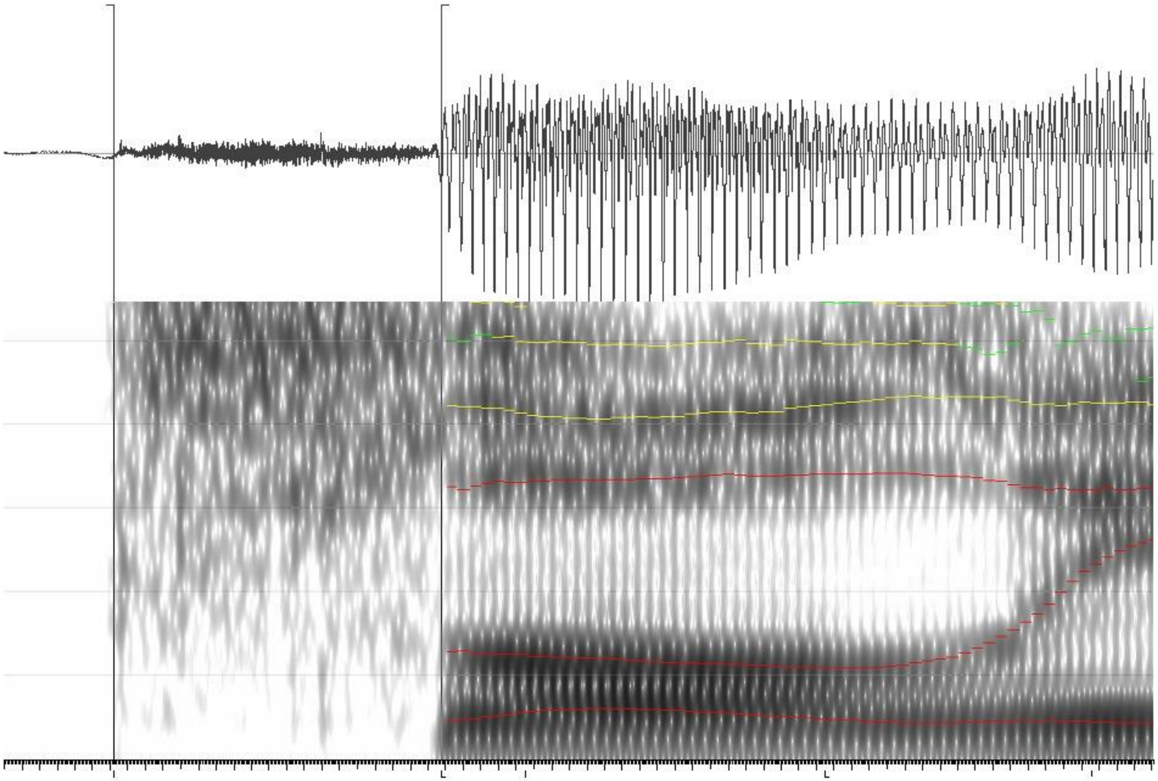
/o/ as in “so”



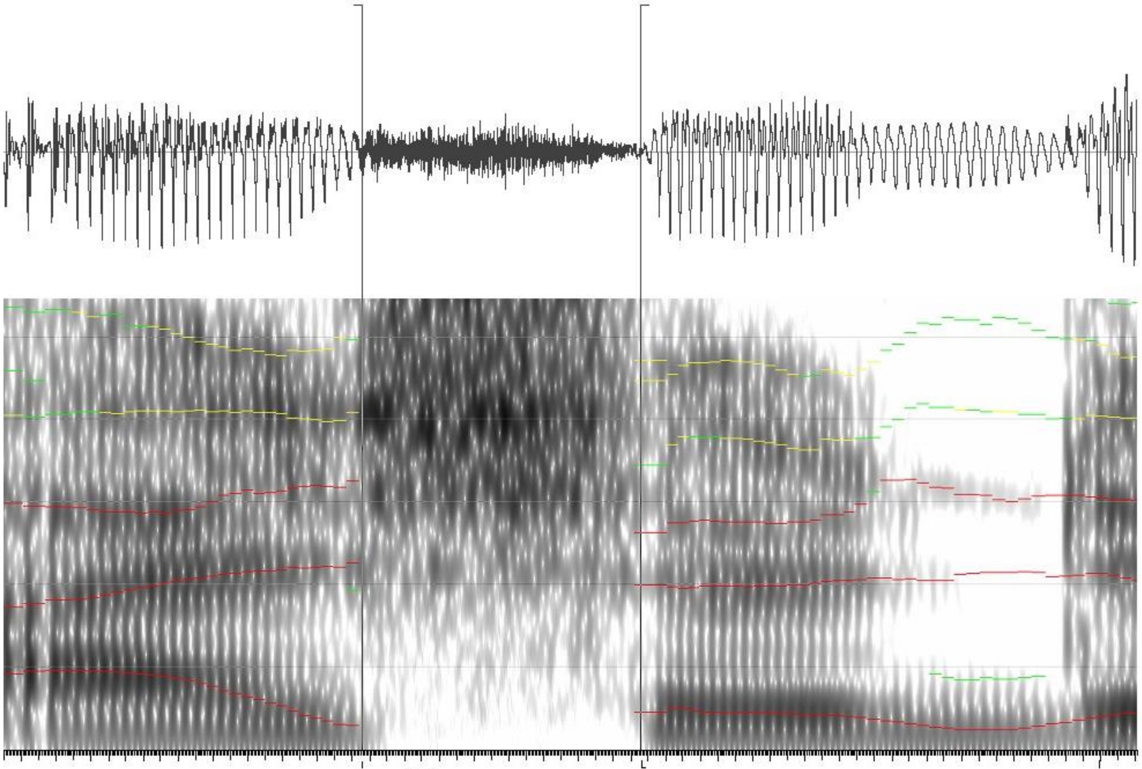
/a/ as in “stop”



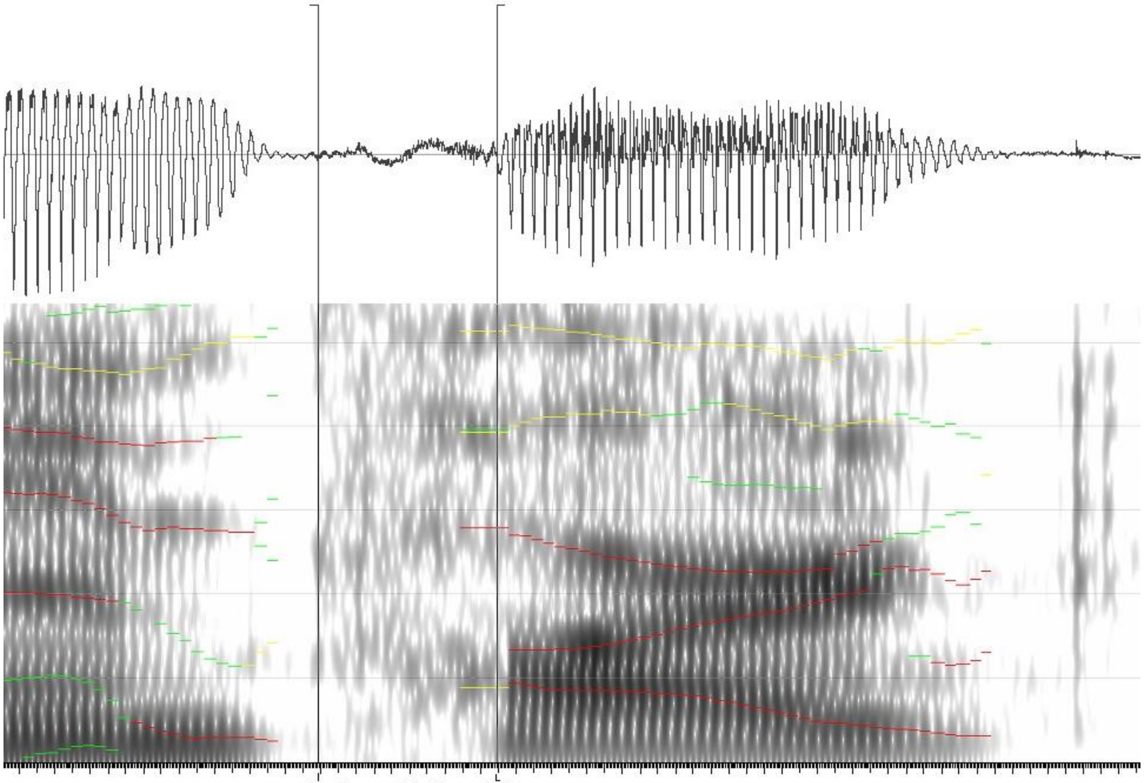
/f/ as in “front”



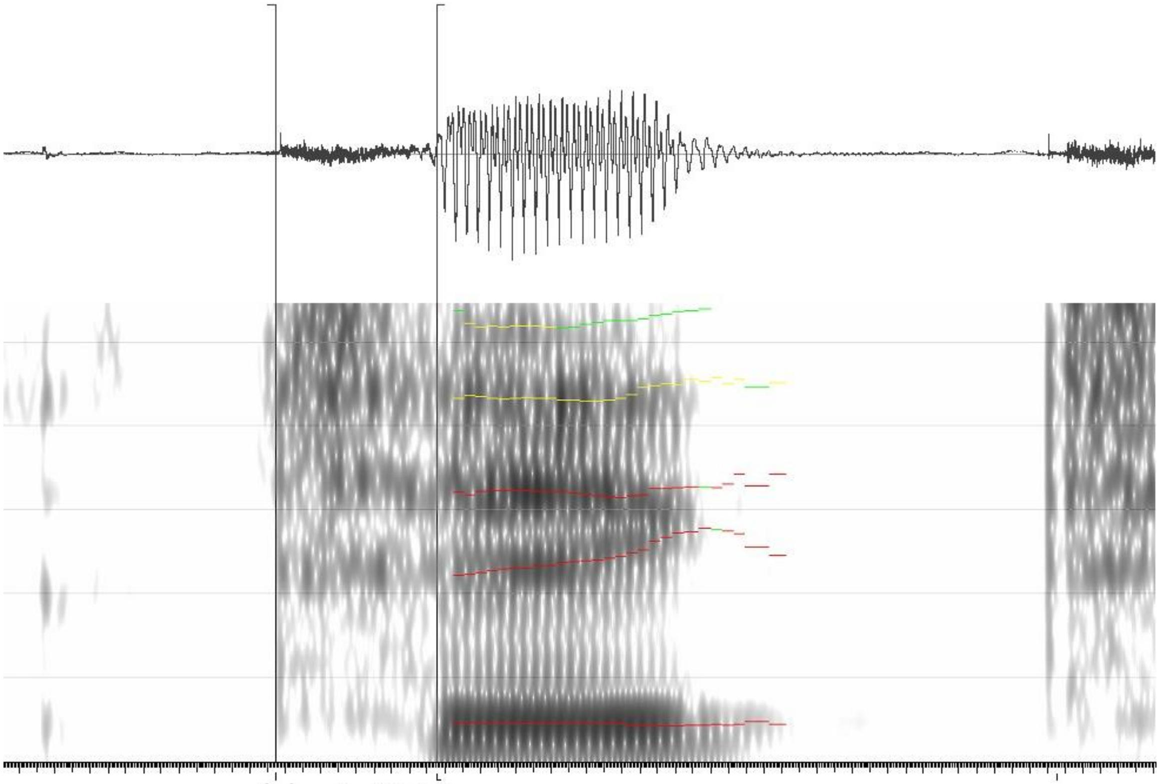
/s/ as in “slowly”



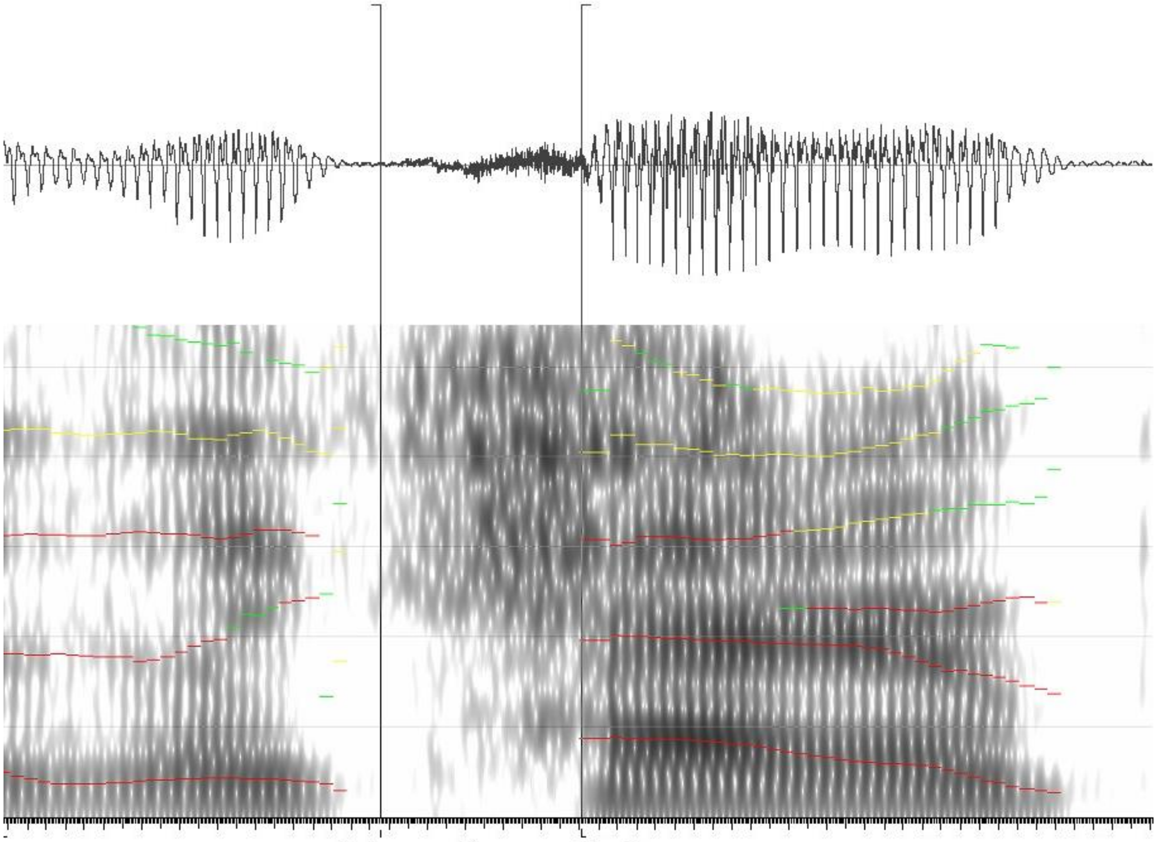
/ʃ/ as in "sure"



/p/ as in "park"

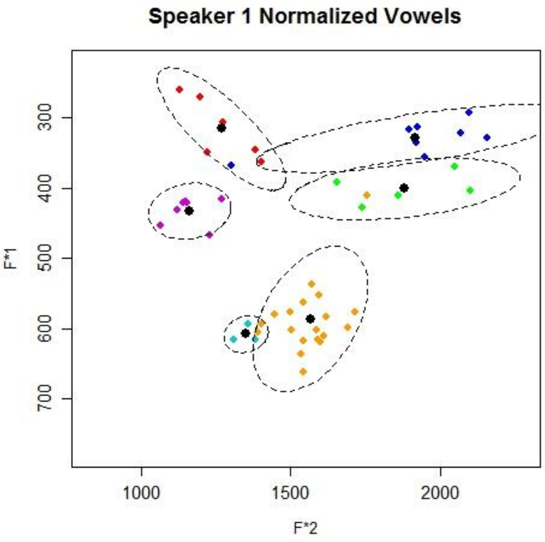


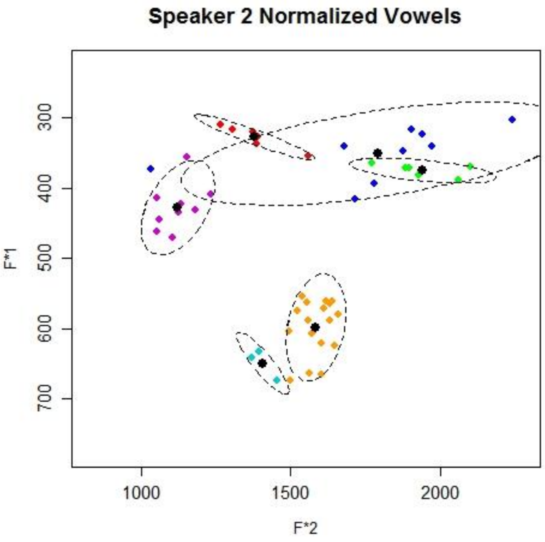
/t/ as in "tick"

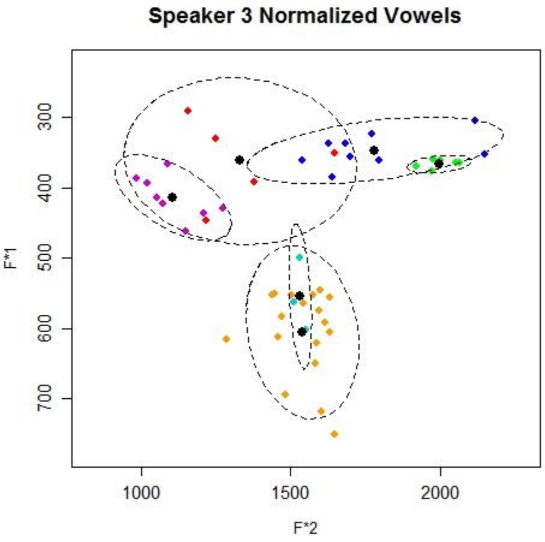


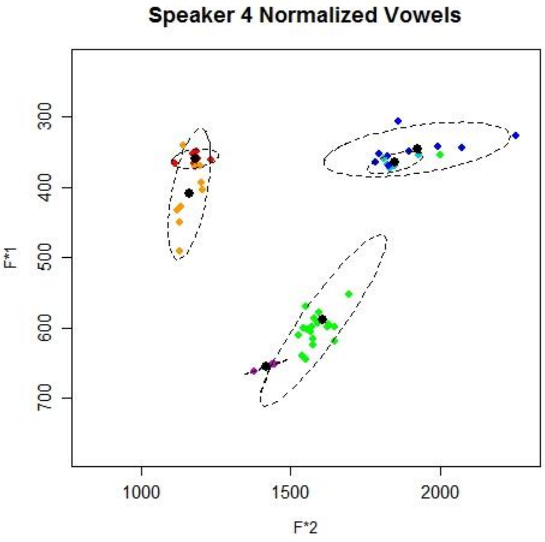
/k/ as in "caterpillar"

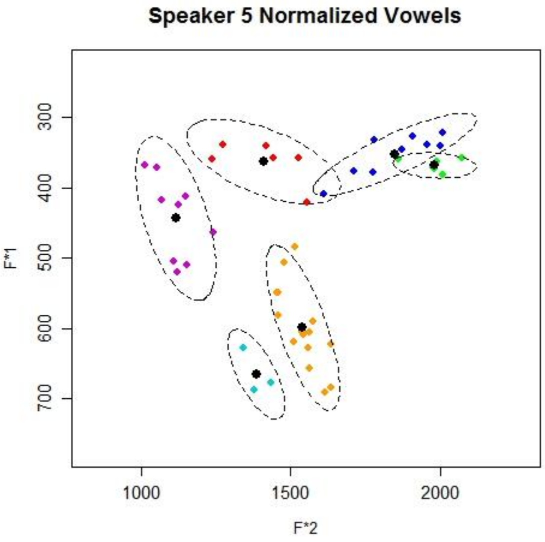
APPENDIX B

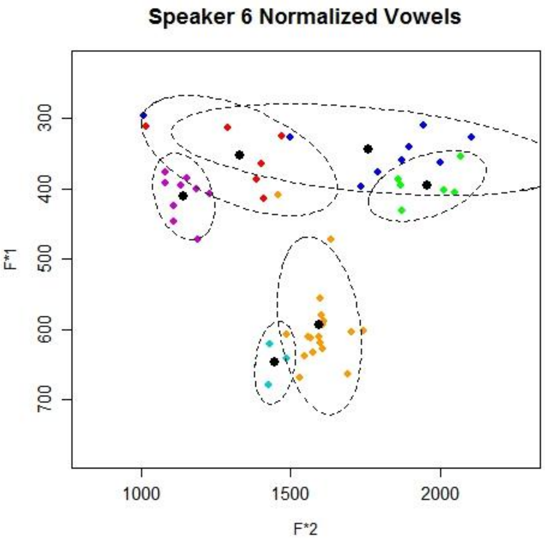

Speaker 1 Normalized Vowels

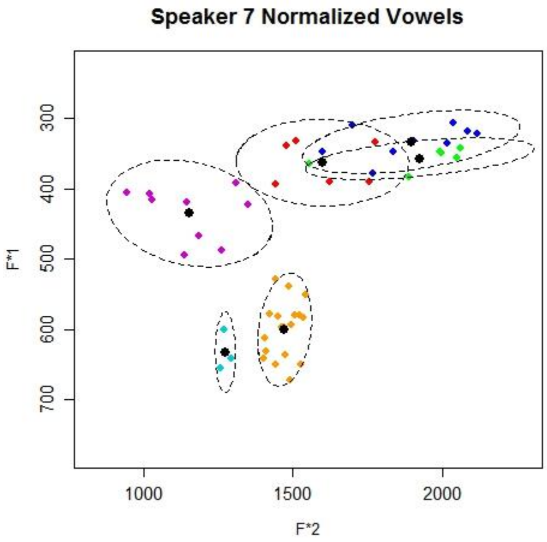

Speaker 2 Normalized Vowels

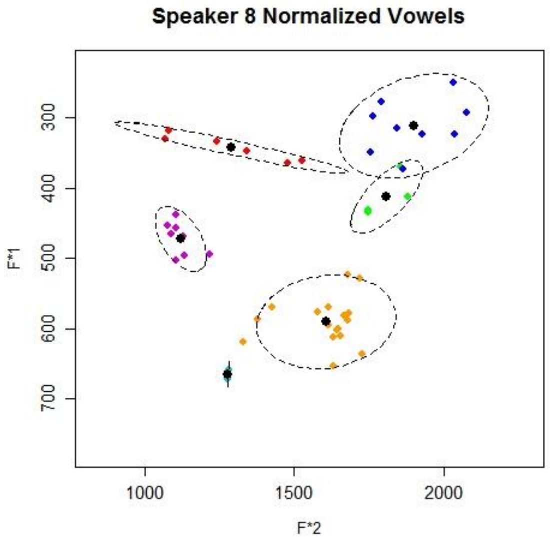

Speaker 3 Normalized Vowels

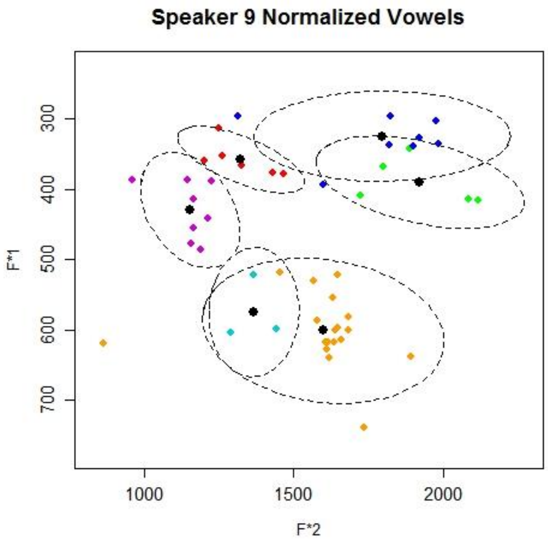

Speaker 4 Normalized Vowels

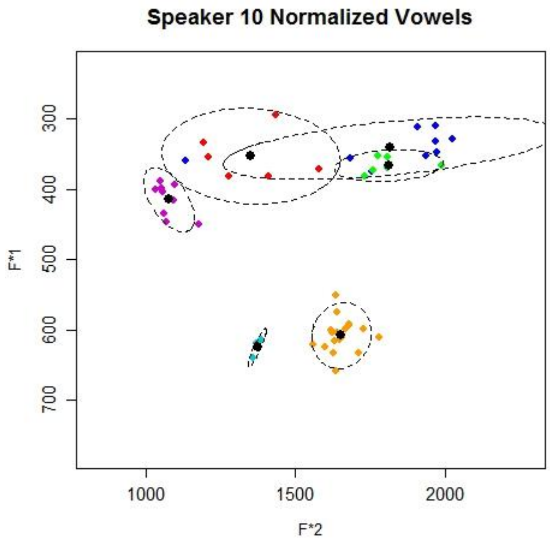

Speaker 5 Normalized Vowels

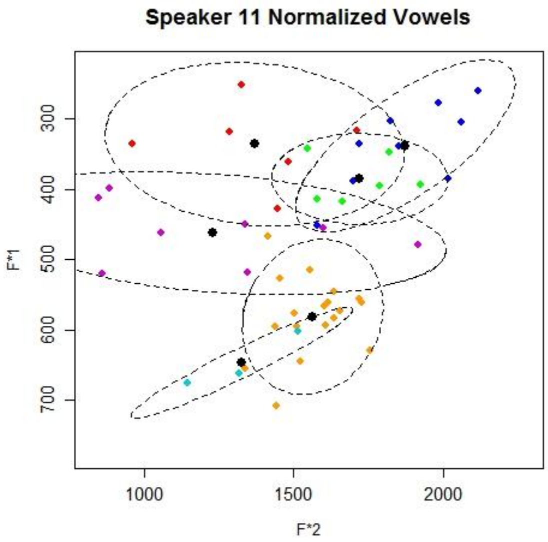

Speaker 6 Normalized Vowels

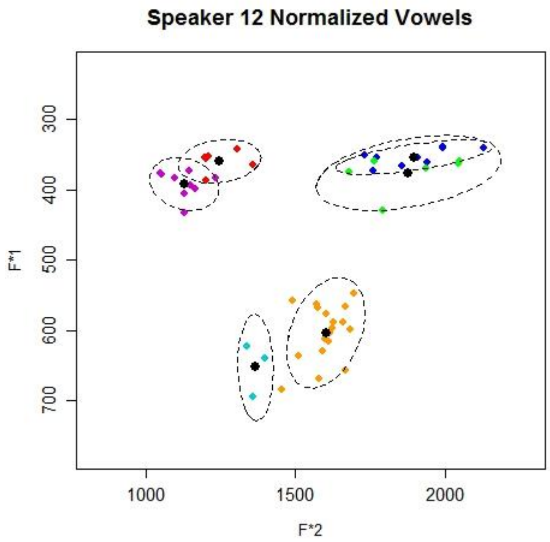

Speaker 7 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2

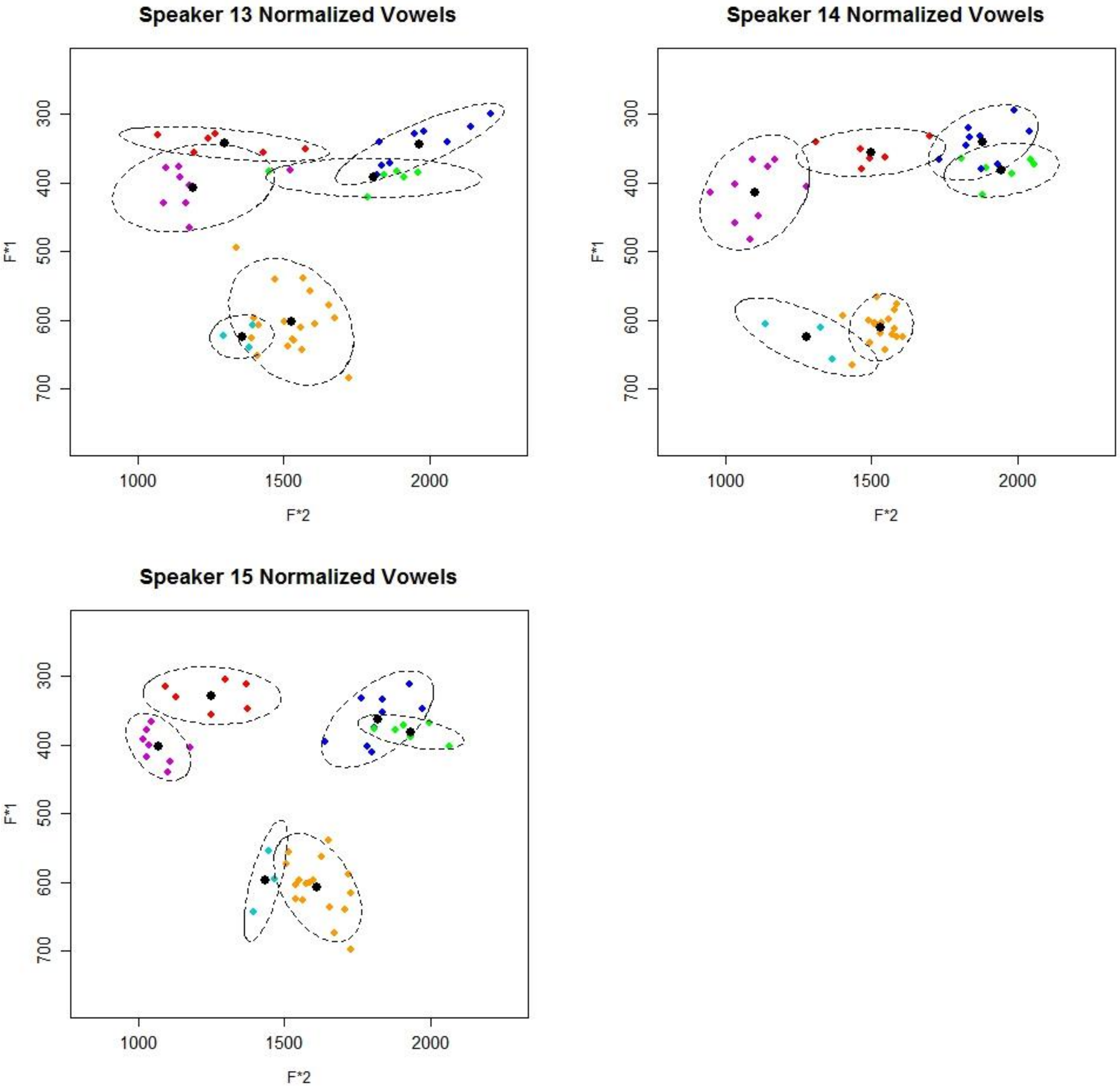

Speaker 8 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2


Speaker 9 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2


Speaker 10 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2


Speaker 11 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2


Speaker 12 Normalized Vowels
300
400
500
600
700
F*1
1000
1500
2000
F*2



F1-F2 format plots showing normalized vowels. Values are in Hz, but have been normalized to allow cross-speaker comparisons. Increasing F2 values on the x-axis correspond with more anterior positions of the primary tongue-to-palate constriction. Decreasing F1 values (moving upward along the y-axis) correspond with increases in the height of the tongue. Different colored data points reflect different vowels. These figures indicate that while average normalized values are roughly equivalent across speakers, there are notable differences in vowel-specific variability between speakers within the time condition.