2017-06-01

Perceptual Analysis of Children's Adaptation to an Electropalatography Sensor

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

Master of Science

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ABSTRACT

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The purpose of this study is to observe children's adaptation to an electropalatographic (EPG) sensor. Sound recordings of six children between the ages of 7;0 and 9;11 sampled at 30-minute intervals over a two-hour period of wearing an EPG sensor were perceptually evaluated to quantify the children's adaptation over time. Twenty native speakers of American English evaluated the pronunciation of a series of words with embedded stops and fricatives produced with and without an EPG sensor in place. When collapsed over speaker and stimulus type, listener ratings decreased significantly after inserting the EPG sensor. Ratings then increased significantly after the sensor was in place for 30 minutes, and again after 60 minutes. No significant improvement in pronunciation was noted between the 60- and 120-minute test intervals, and adaptation did not reach preplacement levels until the sensor was removed. Mixed results were found in how speakers adapted across the different stimulus types. Adaptation was most consistent across speakers for the conversation conditions, but occurred most rapidly for /s/ and /k/. Speakers showed the best overall adaptation for the phoneme /t/ by the end of testing. These results are similar to several adaptation studies with adults, and the two studies with children. Results from this study will help speech pathologists effectively use EPG technology to help children accurately pronounce speech sounds, and to generalize these pronunciations to their normal speech.

ACKNOWLEDGMENTS

I am grateful for the many people who made this project possible. First, I would like to thank Dr. Nissen for his efforts advising me through all stages of planning, data collection and writing for this thesis, and for his creating the computer program used to collect data in this study. I am also grateful for his allowing me to use his lab, equipment, and software for this research. Secondly, I would like to acknowledge my committee for their insights, and suggestions throughout the research process. Thank you to the students who volunteered to participate as judges for this study, particularly the research assistants who helped pilot the study. I am grateful to my parents who have encouraged me to continue my education and supported me as I worked on my thesis. Finally, I am grateful to my husband for his support, encouragement and insight throughout the thesis process.

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DESCRIPTION OF THESIS STRUCTURE

This thesis was part of a larger collaborative project, portions of which may be submitted for publication, with the thesis author being one of multiple contributing coauthors. The body of this thesis was written as a manuscript suitable for submission to a peer-reviewed journal in speech-language pathology. The analyses conducted in this study were based on a set of recordings originally collected by Nissen, Celaya, & Knapp (2014). An annotated bibliography is presented following the reference section in Appendix A. The consent form used in this study is found in Appendix B.

Introduction

Electropalatography (EPG) is an important technology used to track the shape and movement of the tongue's contact with the hard palate during speech (Gibbon & Paterson, 2006). EPG was originally designed by Samuel Fletcher and consisted of an artificial pseudopalate containing 48 electrodes embedded in a plastic mouthpiece. Information from the electrodes traveled through a series of external wires and was then projected on a light emitting diode (LED) display (Fletcher, McCutcheon, & Wolf, 1975). Current EPG sensors, such as the SmartPalate® produced by CompleteSpeech International® (2015), now have as many as 124 gold-plated electrodes attached to a relatively thin acrylic mouthpiece that is custom molded to the shape of each user's upper teeth and hard palate. Information from the sensor is sent through wires at the front of the mouth to a computer display (CompleteSpeech, 2015). The visual biofeedback provided by the EPG sensor has been found to be a valuable tool in therapy as it helps clients to see where their tongue makes contact with the palate, providing visual feedback on how to adjust their tongue movements to more precisely articulate speech (Carter & Edwards, 2004; Dagenais, 1995; Gibbon & Paterson, 2006; McAuliffe & Cornwell, 2008). Electropalatography technology is also useful in research, as it helps researchers capture lingua-palatal contact patterns in real time (Fletcher, et al., 1975).

Electropalatography has been used to describe and treat speech problems associated with a variety of conditions including cleft palate (Gibbon & Paterson, 2006; Scobbie, Wood, & Wrench, 2004), articulation impairment (Carter & Edwards, 2004; Dagenais, 1995), and phonological impairment (Dagenais, 1995; McLeod & Searl, 2006). Motor speech disorders including apraxia (McAuliffe & Ward, 2006), and dysarthria following traumatic brain injury (Goozée, Murdoch, & Theodoros, 2003; Kuruvilla, Murdoch, & Goozée, 2008; McAuliffe &

Ward, 2006) and dysarthria associated with Parkinson's disease (McAuliffe, Ward, & Murdoch, 2006) have also been evaluated using EPG.

Although EPG is typically used to treat speech, it can also be used to evaluate and treat non-speech motor disorders. For example, a study by Mantie-Kozlowski and Pitt (2014) showed potential for EPG as a tool in helping people with non-speech orofacial myofunctional disorders (NSOMD) to develop better tongue-to-palate contact and lingual control in swallowing. Additionally, speech-language pathologists are not the only professionals interested in EPG. EPG has also been used in research by dentists, orthodontists, and linguists to track the movement of the tongue (McLeod & Searl, 2006).

A client's ability to adapt to the EPG device is an important consideration in EPG treatment. Any structural change to the oral cavity, including foreign objects in the mouth, has the potential to alter normal speech production. For example, a five-year-old child who loses his two front teeth or a teenager who was just fitted with an orthodontic retainer may require an adjustment period as they adapt to the physical changes or obstructions in their mouth (McFarland, Baum, & Chabot, 1996). Likewise, speakers may need time to adjust to the EPG. Although relatively thin (1-2 mm) (Cheng, Murdoch, Goozée, & Scott, 2007; Hamlet & Stone, 1982; McAuliffe, Robb, & Murdoch, 2007; McLeod & Searl, 2006), the EPG sensor decreases the height of the hard palate, thus changing the structure of the oral cavity (McFarland et al., 1996). Speech pathologists need to be aware of the differences in speech produced by structural changes resulting from the EPG. Additionally, they need to be aware of the adaptation time necessary for the client to produce speech that resembles their natural speech as closely as possible.

Previous research on speakers' adaptation to non-EPG devices such as bite blocks and lingual magnets may provide insights into how people respond and adapt to a perturbation in the oral cavity. Bite blocks are material placed between the teeth to set the jaw opening to a fixed position during speech (McFarland et al., 1996). Speakers usually open and close their mouths to varying degrees as they speak; however, bite blocks hold the jaw in one place, thus limiting its range of motion (McFarland et al., 1996). The effects of a bite block on speech may vary according to phoneme. A study by McFarland and Baum (1995) found that a bite block made significant changes to the spectral characteristics of vowels, stops, and fricatives immediately following placement of the bite block. After subjects participated in a 15-minute conversation with the bite block in place, the formant frequency and duration of vowels returned to normal, or near-normal levels, but spectral characteristics of consonant productions were still significantly different from the normal-speaking condition. McFarland and Baum concluded that speakers can learn to adapt vowel production to a bite block, but consonants require a much longer adaption time if the speaker is to adapt at all (McFarland & Baum, 1995).

The adaptation of vowel production observed by McFarland and Baum may be explained by a compensatory behavior called *super shaping* observed by Gay, Lindblom, and Lubker (1981) in a study on vowel production in the presence of a bite block. The researchers found the greatest amount of articulator compensation in areas where the greatest lingua-palatal constriction occurs in normal speech. That is, the speaker's efforts were concentrated on these areas of highest constriction, and, as a result, these areas more closely approximated normal positioning than did areas of less constriction despite the bite block (Gay et al., 1981).

Lingual magnets are another technology used to track speech movements. Although lingual magnets are much smaller than bite blocks, they still pose concern for interference with

normal speech. However, a study done on the use of a magnetic pellet to track tongue movement showed no significant difference in spectral characteristics of speech in the fricatives /s/ and /ʃ/ produced with or without the magnet (Dromey, Nissen, Nohr, & Fletcher, 2006). A later thesis (Hunter, 2016) studied speakers' adaptation to two sensor coils placed on the midline of the tongue: one on the tongue tip, and one in the center of the tongue. Three other coils were attached to the teeth, and upper and lower lips. This study found that perceptual ratings of articulatory precision decreased after the coils were placed. Acoustic measures showed a shorter duration following placement of the coils, and the spectral spread and center of gravity increased for /ʃ/ and decreased for /s/. Differences in acoustic and perceptual measures were fairly constant after the speakers had worn the sensors for 10 minutes, but did not return to preplacement levels (Hunter, 2016). The difference in results found in the study by Dromey et al., and Hunter may be a result of an increased number of sensors used in Hunter's study.

Although studies on speaker adaptation to bite blocks and lingual magnets provide valuable insight into how speakers compensate for obstructions in their oral cavity, the structure and purpose of these devices are different from those of an EPG sensor. Bite blocks are placed between the teeth to hold the jaw in one position (McFarland et al., 1996), and lingual magnets are attached to the tongue to track tongue movement in the oral cavity (Dromey et al., 2006). Electropalatography sensors, on the other hand, cover the hard palate and allow the jaw to move freely while tracking tongue contact with the palate (McFarland et al., 1996).

Studies on an individual's ability to adapt to orthodontic retainers are similar to studies showing the effects of an EPG device. Hamlet and Stone (1982) conducted a study to determine if a history of lisping was related to difficulty adapting to a dental retainer. The researchers used an EPG sensor the same size as a dental retainer to record the participants' articulation patterns

before and after wearing the retainer for two weeks. They found that participants did not adapt to the sensor if they maintained the same articulator adjustments as when the retainer was initially inserted. The participants who adjusted their articulation throughout the two-week period showed better adaptation at the end of the study. These results provide some evidence that people adapt to oral obstructions in different ways, and that some of these adaptations may be more effective than others (Hamlet & Stone, 1982). Since dental retainers have a similar shape and placement to EPG sensors, this speaker-by-speaker variation should be considered when evaluating an individual's ability to adapt to EPG.

Like dental retainers, palatal appliances resemble the effects of EPG sensors on speech more closely than technologies such as bite blocks and lingual magnets. Searl, Evitts, and Davis (2006) described the difference between palatal appliances and EPG devices: ". . . palatal appliances usually only cover one portion of the hard palate (typically the alveolar ridge), the thickness is not uniform, and the maximum thickness is often much greater (3-6mm) than that used in EPG and contact pressure studies" (p. 108). Following the methodology of McFarland and Baum (1995), McFarland et al. (1996) conducted a study of adaptation to a palatal appliance. Their findings indicated that the palatal appliance showed little acoustic or perceptual effect on the production of vowels. Stops showed some acoustic, but not perceptual differences between speech with the EPG sensor, and speech without. However, the researchers did find perceptual differences for the fricative /s/ when the palatal appliance was worn. In particular, listeners rated their ability to identify the sound, and the quality of the sound lower for /s/ immediately after the palatal appliance was placed; they rated quality, but not their ability to identify the sound, lower after speakers had participated in a 15-minute conversation. In summary, vowels were the least affected by a palatal appliance, followed by stops, and then fricatives (McFarland et al., 1996).

Several studies have investigated how adults adapt their speech to the presence of an EPG sensor (McAuliffe et al., 2007; McLeod & Searl, 2006; Searl et al., 2006). Adaptation times found in these studies varied from 30 minutes to three hours depending on the speech sounds being evaluated and the criteria for adaptation. McAuliffe et al. used a *practise palate*—an EPG without electrodes—to study adults' adaptation to an EPG sensor. McAuliffe et al., found that initial imprecision can be detected perceptually immediately after insertion of the device; however, adaptation typically occurs 45 minutes to three hours postplacement. Additionally, acoustic measures showed that the segment duration of consonants, and the frequency of vowel formants are not significantly affected by the practice palate, but the first spectral moment was reduced for all productions of /s/ regardless of how long the participant had been wearing the practice palate. Although the practice palate used in this study did not have sensors like an actual EPG device, the thickness and shape of the practice palate was identical to that of the EPG sensor. Therefore, studies involving practice palates can be used to predict adaptation to EPG. In fact, both EPG and practice palates have shown similar changes to the acoustic characteristics of consonants (McLeod & Searl, 2006).

Searl et al. (2006) studied the acoustic and perceptual effect of an EPG sensor on speech. In this study, speakers adapted to their EPG sensor in about 30 minutes after placement as manifest by the acoustic measures returning to preplacement levels. The highest levels of difference in spectral mean, and stop-gap duration were observed at 15 and 30 minutes postplacement. Although differences were observed in acoustic measures, they were not manifest in the perceptual measures. Listeners identified the target phoneme with at least 98 percent accuracy for every test, and mean distortion ratings were between one and six percent. Searl et al. claimed that little or no adaptation time is needed for people to produce perceptually

undistorted consonants with a 0.5 mm pseudopalate; and acoustically accurate productions occur after the participant has worn the pseudopalate for about 30 minutes.

In a study on acoustic and perceptual adaptation to an EPG sensor, McLeod and Searl (2006) found that general adaptation occurred for /t/ after about one hour, and /s/ after two hours; however, no speaker produced speech that acoustically matched the no-palate condition. McLeod and Searl noted that overall, the palate had only a small effect on perceptual distortion ratings, with affricates and fricatives being most notably affected. Findings from McLeod and Searl differ from the study by Searl et al. (2006) which reported that acoustic measures reached preplacement levels. According to these studies on adult adaptation to EPG, adaptation can occur anywhere between 30 minutes and three hours after the palate is inserted. The adaptation time can vary depending on phoneme and speaker. Additionally, adaptation time can vary based on adaptation criteria (i.e., acoustic or perceptual); that is, a subject's rate of adaptation as judged by a listener is typically recorded as happening more quickly and completely than the acoustic measures of adaptation for the same subject (McAuliffe et al., 2007; McLeod & Searl, 2006; Searl et al., 2006).

Most EPG adaptation studies have described how adults adapt to the presence of the EPG sensor; however, children are also an important population that can benefit from EPG therapy. A 2006 study by Gibbon and Paterson surveyed 10 speech-language therapists about the use of EPG in therapy. Therapists were asked to include information concerning demographics, type of disorder, therapy given, and effect of EPG on the client's progress. Of the 60 clients that the therapists reported as using EPG in therapy, 51 percent began therapy with an EPG device between the ages of six and ten and 81 percent started before the age of 15 (Gibbon & Paterson, 2006).

Although children make up a large proportion of EPG users, relatively little research has examined how younger speakers adapt their speech to the presence of the sensor. Two unpublished theses by Knapp (2014) and Celaya (2014) examined children's adaptation to an EPG sensor by evaluating the acoustic characteristics of stop and fricative productions. Six children were recorded saying words containing the sounds /t/, /k/, /s/, and /ʃ/ without the EPG sensor in place, at five, 30-minute intervals while wearing the EPG sensor, immediately after the sensor was removed, and 30 minutes following removal. Knapp (2014) noted that for the phonemes /t/ and /k/, acoustic measures at the end of testing with the sensor (two hours postplacement) resembled preplacement levels for three of the six participants; two of the six participants showed partial adaptation to the sensor. An acoustic analysis of /s/ and /ʃ/ completed by Celaya indicated that the child speakers adapted to the EPG sensor within 30 minutes to two hours. The timing and consistency of adaptation varied by spectral characteristic. Fricative duration was least affected by the presence of the EPG sensor, whereas the fricative intensity was often impacted by the sensor, a decrease after placement of the EPG followed by a gradual increase throughout the two hours. Spectral mean and variance were both affected upon placement of the EPG sensor, and some participants began to adapt by 30 minutes postplacement; however, measures of mean and variance were more variable across speakers, and adaptation was less consistent across the two hours of testing than for spectral intensity (Celaya, 2014).

The work by Knapp (2014) and Celaya (2014) provides insight into how children might adapt to an EPG sensor in terms of speech acoustics; however, little research has examined children's adaptation in terms of the perceptual salience of their speech production. Thus, the

current thesis seeks to expand the previous research of Knapp (2014) and Celaya (2014) by using a perceptual analysis to quantify children's adaptation to EPG over time.

Method

Participants

Participants for this study consisted of 25 university students enrolled in the Department of Communication Disorders at Brigham Young University (BYU). Data from four participants was excluded from the study due to an intra-rater reliability coefficient of less than .50, and one participant for limited linguistic experience. Before testing, participants' hearing was screened via pure-tone air-conduction testing at 25 dB across one-octave intervals from 500-8000 Hz. In addition, all participants signed a consent form prior to testing. Procedures for this study have been reviewed and approved by the institutional review board at BYU.

Stimulus

Stimulus items for this study were extracted from audio recordings collected by Knapp (2014) and Celaya (2014). The target stimuli in these studies were produced by eight children between the ages of 7;0 and 9;11 years. Speakers were asked to say target words in the carrier phrase *Say ___ again* three times, and then to respond to a question asked by the examiner. Speakers completed this task at eight intervals throughout a three-hour session: (a) prior to placement of an EPG sensor, (b) directly after inserting the EPG sensor, (c) after 30 minutes of wearing the sensor, (d) after 60 minutes, (e) after 90 minutes, (f) after 120 minutes, (g) immediately after the sensor was removed, and (h) 30 minutes after removing the sensor. All audio recordings were collected in a sound-attenuating booth using a high-quality, low-impedance dynamic microphone and preamplifier. Recordings were made with a sampling rate of 44.1 kHz and a quantization of 16 bits.

Stimulus items in the current study included a portion of the recordings collected by Knapp and Celaya. The speech samples consisted of 768 individual sentence files (eight participants x eight test intervals x four stimulus words x repeated three times). The stimulus words included the sounds /t/, /k/, /s/, and /ʃ/ in the initial position followed by a high-front vowel. One of the three repetitions of each word was randomly selected for perceptual analysis resulting in a total of 256 words. Stimuli also included 64 conversation samples (eight participants x eight test intervals).

In preparation for perceptual analysis, words were extracted from the carrier phrases using Adobe Audition (Version 9). Then words were normalized for intensity, and filtered to extract any electronic noise and noise artifacts. Additionally, 500 ms of silence was added before and after each word. The conversation samples were modified to remove the examiner's comments and edited to be approximately 30 seconds long, with an electronic beep signaling the end of each sample.

Procedures

The listeners evaluated the extracted speech samples in one 60-minute session, divided into three test periods. They evaluated the stimuli with word-initial fricatives in a 15-minute test period, stimuli with word-initial stops in another 15-minute period, and the conversation samples in a 30-minute period. The three tests were administered in a random order, and participants were offered a two-minute break after 30 minutes. The session began with a hearing screening and instructions.

Audio signals for both tests were presented to the participants via headphones. The participants were allowed to select a comfortable intensity for the stimuli with a starting level of approximately 60 dB HL. The system did not permit intensities outside the range of safe hearing.

Before presenting the test stimuli, each participant evaluated a practice trial of each stimulus type

to ensure that they understood the rating system and that the equipment was adjusted properly.

Testing for stimulus words. Participants were instructed to listen to the initial consonant

of each word presented and then rate their perception of the correctness of the consonant

production using a sliding analog scale from 0 to 100 (0 corresponding to a completely distorted

production and 100 corresponding to a typical, undistorted production). Participants were

provided with written instructions including the two words they would hear for that particular

test, and directions for using the scale. Using a custom computer program, all recordings were

presented to participants in a random order. After rating a production, participants were

instructed to advance to the next stimulus item by using the mouse to select a small box on a

computer screen. Participants were informed that they could replay an item if they missed

hearing the stimuli due to an external distraction or technical error, but the test was not designed

for multiple repetitions of each stimulus.

Testing for conversations. Participants were instructed to listen to each conversation,

and then rate the overall intelligibility of the conversation from 0 to 100 (0 corresponding to

completely unintelligible, and 100 corresponding to typical, intelligible speech) by using the

same analog sliding scale as in the previous session. Participants were instructed to wait for a

beep signaling the end of the conversation before proceeding to the next item. After rating the

conversation, participants were instructed to advance to the next stimulus item by using the

mouse to select a small box on the computer screen.

Intra-rater reliability. Ten percent of the stimulus items were retested for each listener.

The ratings for the first and second presentation of the stimulus were compared using a Pearson

Correlation. Four participants received a correlation of less than 0.5 and were excluded from the

study. There was a correlation [$r^2 = .817$, $p = 0.01$] between the scores of the remaining participants indicating that the participants included in this study showed statistically significant reliability for the ratings they provided.

Results

Inferential statistics for this study involved a repeated-measures analysis of variance (ANOVA) with three within-subject factors (speaker, time period, and stimulus type). The ANOVA results include a measure of effect size, partial eta squared, or η^2. The value of this power statistic (η^2) can range from 0.0 to 1.0, and is considered a proportion of variance explained by a dependent variable when controlling for other factors. Greenhouse-Geisser adjustments were used to adjust the F-tests with regard to the degrees of freedom when significant deviations from sphericity were present. In addition, pairwise comparisons for significant within-subject factors were calculated using General Linear Model repeated-measures contrasts with associated F-tests.

Time

According to the results of the ANOVA, when the listener ratings were collapsed across speaker and stimulus type, the difference in average ratings between time periods was statistically significant, $F(7, 133) = 169.96$, $p < .001$, $\eta^2 = .90$. As illustrated in Figure 1, there was an overall decrease in pronunciation clarity upon insertion of the EPG sensor, with a gradual increase in clarity until 60 minutes postplacement. At 60 minutes, the improvement plateaued below preplacement levels. Ratings returned to preplacement levels once the EPG device was removed. Results of the pair-wise comparison support the trend illustrated in the graph. The comparison showed a significant difference between the ratings before and immediately after the EPG was inserted, $p < .001$, with a mean difference of 34.52. Listener ratings increased

significantly from the time the EPG was placed, and 30 minutes postplacement, $p < .001$, with a

mean difference of -7.17. Ratings continued to increase between 30 and 60 minutes

postplacement, $p < .001$, with a mean difference of -6.39. The difference between tests at 60, 90

and 120 minutes postplacement was not significant, suggesting that adaptation to the EPG

plateaued, or stopped after 60 minutes. Ratings did not increase again until the EPG was

removed, as indicated by a significant difference between ratings 120 minutes postplacement and

immediately after removal of the sensor, $p < .001$. The pair-wise comparison also showed no

significant difference among the three tests with the sensor removed.
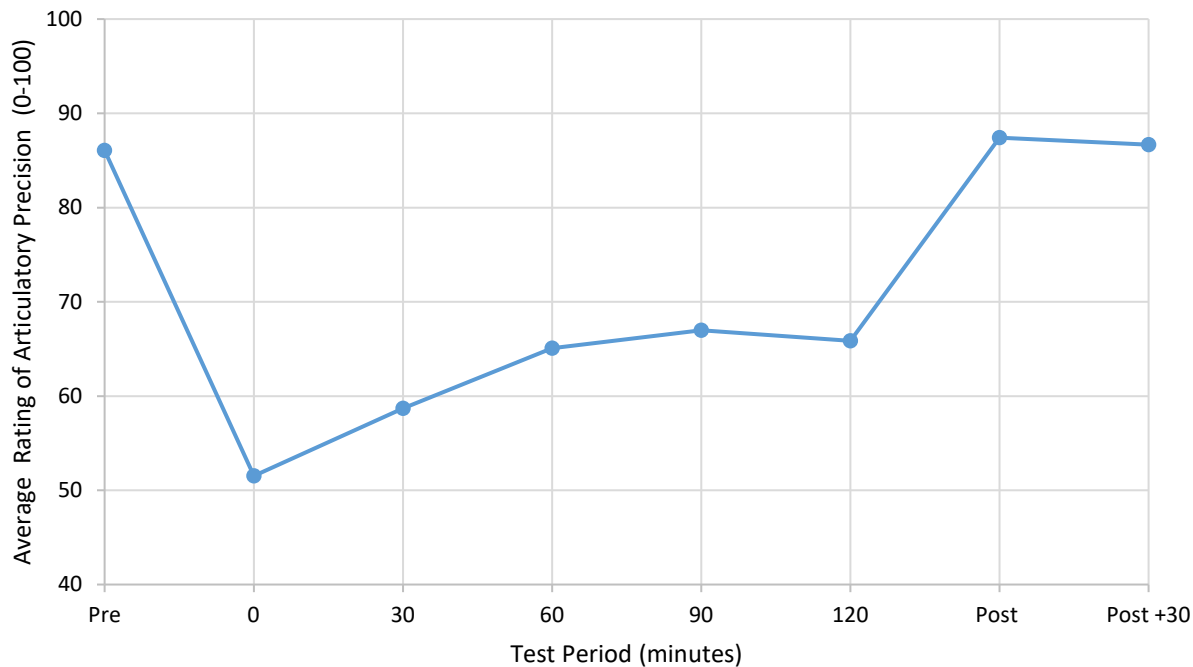
Figure 1. Average listener rating over time with EPG sensor in place. The average listener rating of articulatory precision on a scale from 0 to 100 over the eight time periods. Ratings are collapsed across speaker and stimulus type.

Time-by-Speaker

The ANOVA also indicated a significant interaction between the listener ratings at each

time period and the individual speakers, $F(49,931) = 30.28$, $p < .001$, $\eta^2 = .61$. As shown in

Figure 2, all speakers followed the pattern of an initial decrease in speech clarity following EPG placement; however, the magnitude of this decrease varied depending on the speaker. For example, Speaker 5 dropped 71 average rating points upon insertion of the EPG sensor (Preplacement = 95.2; Time Period 0 = 24.0), while Speaker 6 dropped only 11 points between the preplacement condition (86.3) and immediately after the palate was placed (75.3). Five of the eight speakers showed some adaptation, as manifest by an increase in listener ratings by 30 minutes postplacement, while ratings for the other three speakers continued to decrease until 60 minutes postplacement.

Patterns for listener ratings between 60 and 120 minutes postplacement varied by individual speaker. Ratings for Speaker 2 plateaued, and ratings for Speaker 3 gradually increased between 60 and 120 minutes of wearing the palate—similar to the average pattern seen when observing ratings collapsed over speaker and stimulus type. The other six speakers showed no additional improvement in the clarity of their pronunciation after 90 minutes of wearing the sensor.

The extent to which each speaker adapted to the EPG sensor varied as well. Ratings for Speaker 5 increased by 22 points over the time the EPG was in place (Time Period 0 = 24.0 and Time Period 120 = 46.3). On the other hand, Speaker 6 gained only 2.8 points while the EPG was in place (Time Period 0 = 75.3 and Time Period 90 = 78.1). Despite these differences, all speakers returned to preplacement levels after removal of the EPG sensor.

Time-by-Speaker-by-Stimulus Type

Results from the ANOVA showed that the time-by-speaker ratings also varied as a function of the stimulus type, $F(196, 3724) = 6.17$, $p < .001$, $\eta^2 = .25$. Table 1 contains a detailed

listing of the listener ratings across speaker, time period, and stimulus type. An illustration of these differences is shown in Figures 3a-3h.

Conversation. Average ratings were the most consistent across speakers for the conversation sample condition. Figures 3a-h illustrate that most speakers showed a drop in ratings when the sensor was inserted, followed by a gradual increase while the palate was in place and a return to preplacement clarity when it was removed. The only exception was Speaker 5 (Figure 3e) whose ratings did not increase over the two-hour adaptation period. Speakers 3, 6, and 8 reached preplacement levels at least once while wearing the EPG sensor.
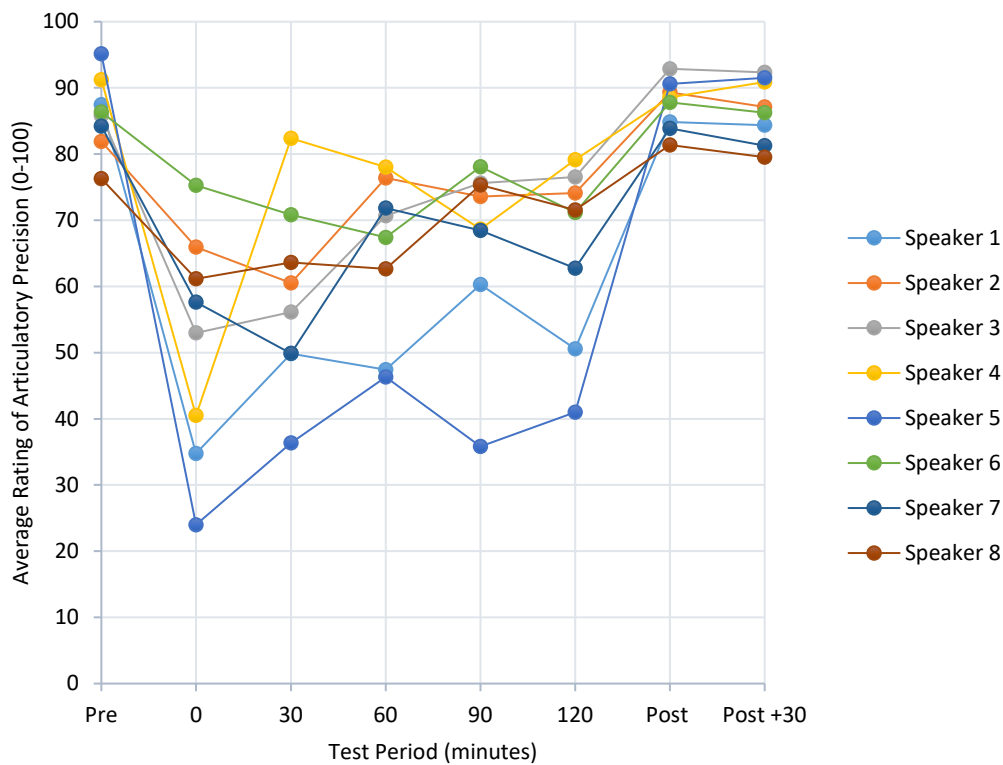
Figure 2. Time-by-speaker interaction. The average listener ratings collapsed across stimulus types for each speaker at each time period.

Table 1

The Mean Rating Each Speaker Received for Each Stimuli at Each Time Period

Speaker	Stim.[a]	Pre	0	30	60	90	120	Post	Post +30
1	Conv.	81.0	33.7	38.9	58.0	56.1	44.6	83.0	82.4
	/k/	93.5	27.5	63.8	55.5	64.9	46.0	91.8	93.5
	/t/	94.9	47.6	53.2	47.1	61.6	63.6	75.1	76.3
	/s/	87.2	15.6	72.3	41.5	68.5	57.1	87.8	87.7
	/ʃ/	80.7	49.3	21.0	35.0	50.3	41.5	86.6	81.9
2	Conv.	78.1	30.5	36.9	46.3	61.5	59.1	80.2	72.9
	/k/	65.5	51.9	78.0	64.5	61.0	76.2	91.7	89.0
	/t/	84.3	77.8	55.7	86.8	63.6	57.1	95.5	93.1
	/s/	91.5	86.9	76.5	94.1	94.3	91.2	85.9	86.2
	/ʃ/	90.1	82.6	55.6	90.3	87.5	87.0	93.4	94.4
3	Conv.	89.4	49.4	41.7	47.8	59.0	87.3	89.7	89.8
	/k/	91.6	70.1	63.6	70.7	73.0	74.9	92.7	94.2
	/t/	89.1	41.7	69.8	80.2	82.2	86.3	96.3	94.8
	/s/	89.3	56.4	56.5	82.6	83.1	75.1	94.0	92.0
	/ʃ/	69.6	47.3	49.2	72.0	80.9	59.0	91.6	91.1
4	Conv.	85.9	31.1	52.8	65.9	58.4	64.6	89.6	84.1
	/k/	95.3	38.2	91.7	90.7	75.3	86.2	89.8	94.6
	/t/	94.0	67.1	93.2	80.1	71.9	95.0	92.9	95.7
	/s/	89.8	33.3	88.4	74.1	68.0	75.8	79.2	88.3
	/ʃ/	91.3	32.8	85.8	79.2	69.7	74.1	91.5	91.6
5	Conv.	93.6	34.1	30.4	40.7	27.0	30.3	95.7	87.7
	/k/	93.4	23.8	25.3	36.9	39.3	46.3	88.7	90.2
	/t/	98.6	13.1	38.1	62.6	49.8	64.4	93.4	96.8
	/s/	97.0	18.4	39.1	32.1	19.6	21.3	83.8	93.9
	/ʃ/	93.2	30.5	48.9	59.2	43.4	42.9	91.5	88.9

Cont.

Speaker	Stim.ᵃ	Pre	0	30	60	90	120	Post	Post +30
6	Conv.	81.0	63.6	76.1	70.2	80.3	77.5	83.9	85.7
	/k/	93.8	78.3	83.4	49.5	85.4	78.4	85.6	92.0
	/t/	82.5	87.7	95.7	85.8	92.6	60.7	86.0	91.0
	/s/	88.2	79.9	50.7	80.5	63.5	69.0	90.5	79.9
	/ʃ/	86.3	66.9	48.3	51.1	68.7	70.2	93.0	82.7
7	Conv.	91.1	57.7	52.6	71.0	79.0	76.2	88.5	83.6
	/t/	88.3	63.6	34.3	65.7	78.3	69.6	91.7	91.7
	/k/	89.3	66.3	60.4	67.2	69.5	56.5	71.5	70.6
	/s/	77.7	37.9	42.4	78.1	43.3	53.9	82.2	72.6
	/ʃ/	74.8	62.8	59.6	77.1	72.1	57.7	85.6	87.9
8	Conv.	84.7	58.0	58.2	59.1	70.9	79.2	82.2	92.9
	/k/	83.6	66.5	77.7	89.9	77.4	86.6	92.3	89.0
	/t/	57.0	69.7	61.4	35.2	68.8	49.2	80.8	52.7
	/s/	84.6	59.5	70.5	77.5	74.9	73.9	81.4	88.7
	/ʃ/	71.4	52.1	50.4	51.6	84.6	68.9	70.1	74.4

Note. ᵃConv. = listener ratings of pronunciation clarity for the 30-second conversation samples.

Figure 3a. Average rating of articulation clarity for each stimulus type over time for Speaker 1.

Figure 3b. Average rating of articulation clarity for each stimulus type over time for Speaker 2.

Figure 3c. Average rating of articulation clarity for each stimulus type over time for Speaker 3.

Figure 3d. Average rating of articulation clarity for each stimulus type over time for Speaker 4.

Figure 3e. Average rating of articulation clarity for each stimulus type over time for Speaker 5.
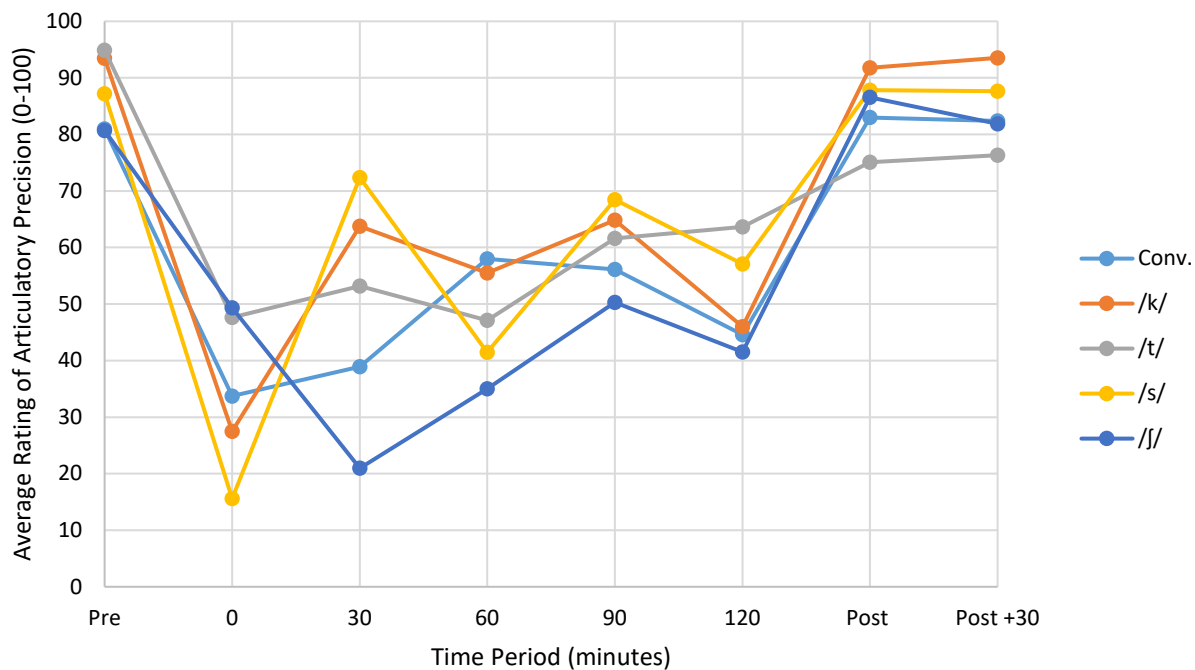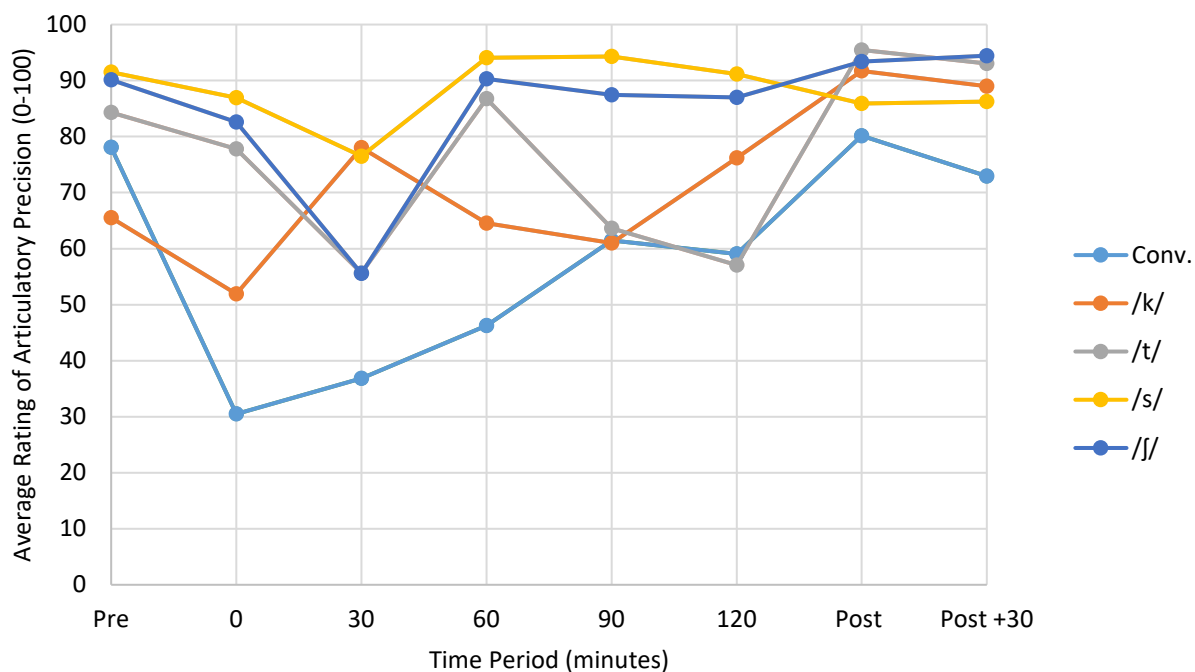

Figure 3f. Average rating of articulation clarity for each stimulus type over time for Speaker 6.

Figure 3g. Average rating of articulation clarity for each stimulus type over time for Speaker 7.

Figure 3h. Average rating of articulation clarity for each stimulus type over time for Speaker 8.
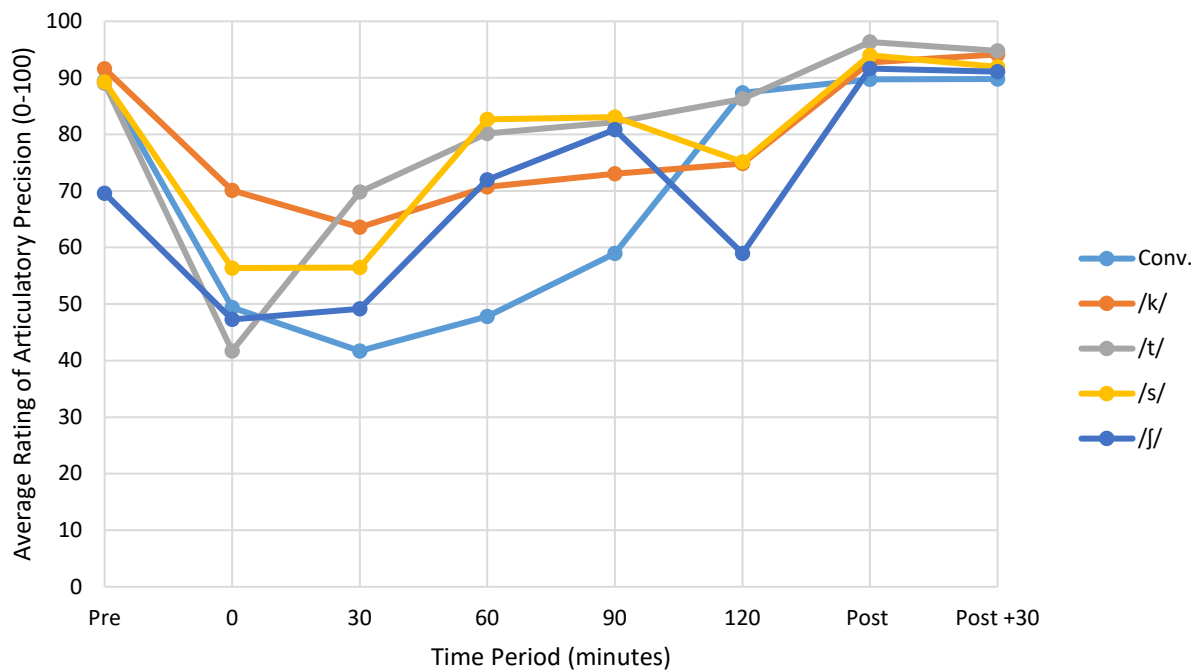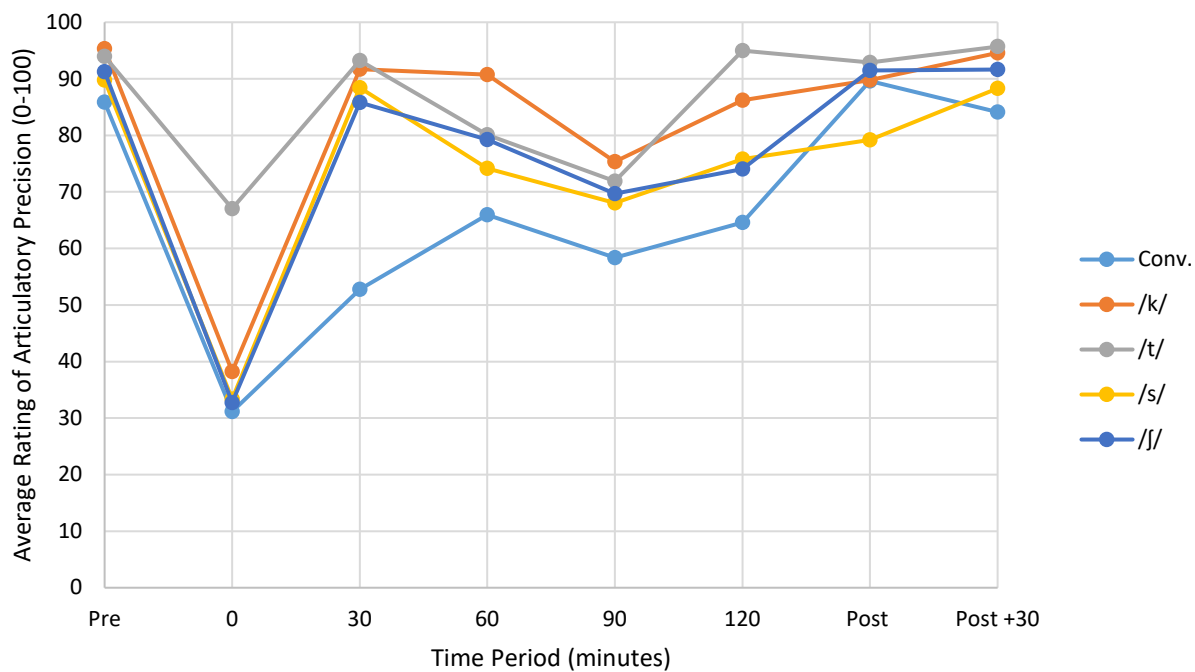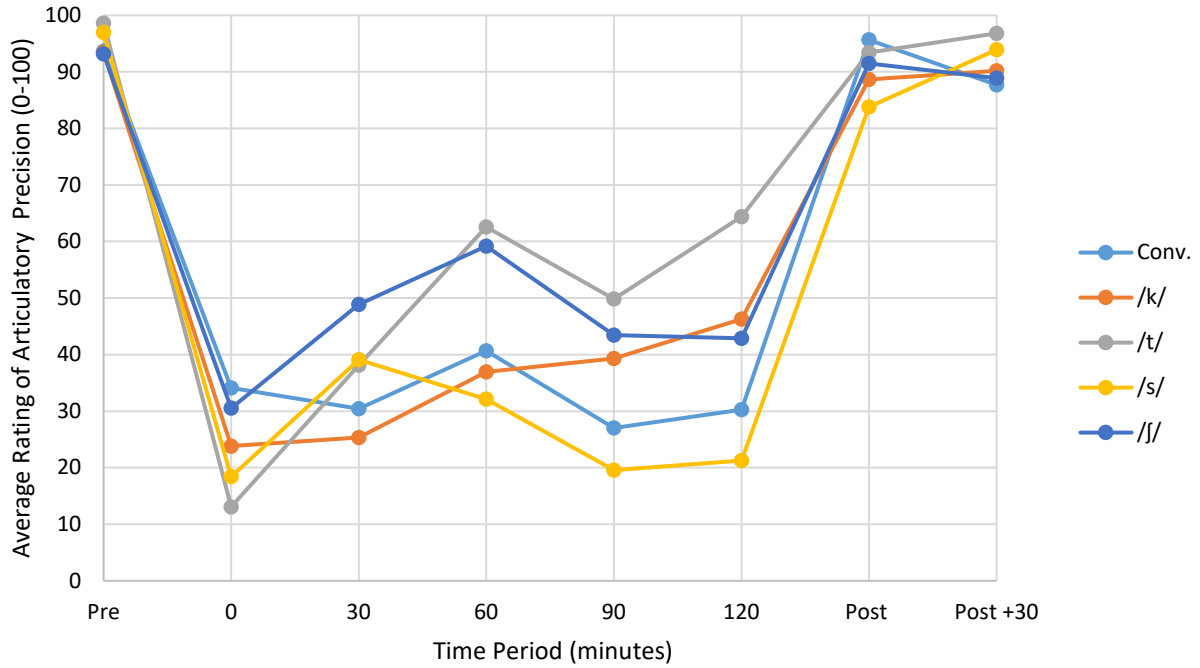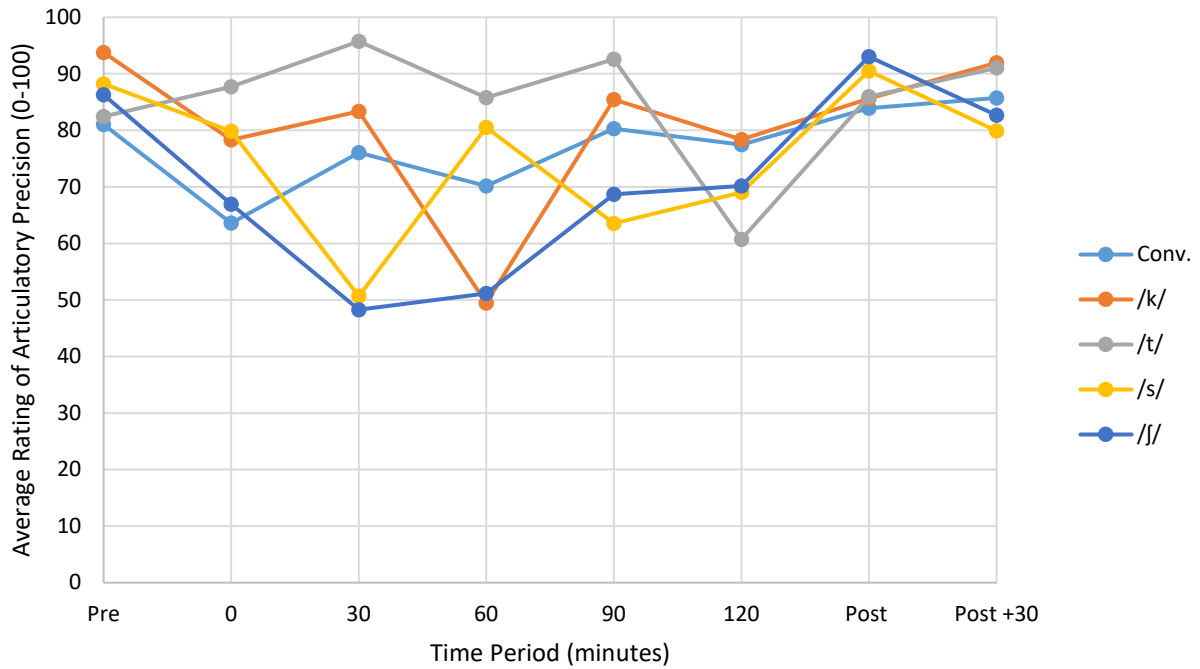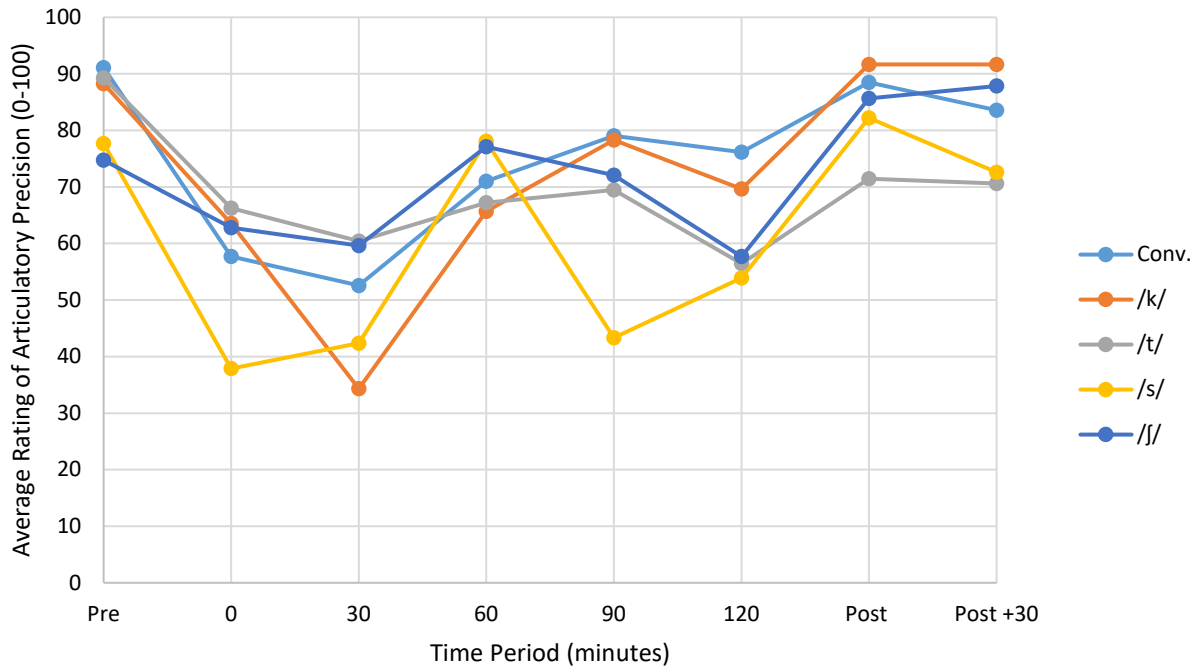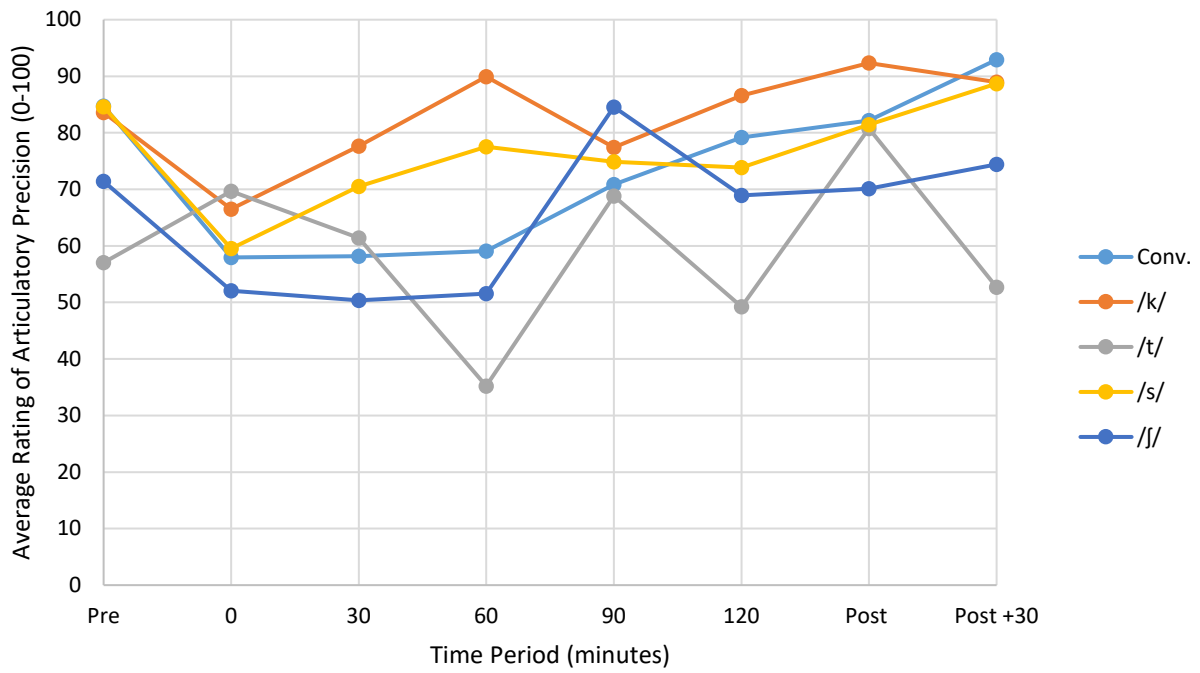
Alveolar fricatives (/s/). Speakers showed an increase in listener ratings for /s/ more quickly than for the other sounds. Six speakers showed an increase in ratings between 0 and 30 minutes of wearing the sensor; however, five of these six showed a decrease in speech clarity during the adaptation period at 60, 90 or 120 minutes. Although listener ratings for Speaker 2 (Figure 3b) initially decreased from 86.9 to76.5 during the first 30 minutes of wearing the EPG sensor, his scores plateaued around his preplacement value (91.5) with ratings of 94.1, 94.3, and 91.2 for tests at 60, 90, and 120 minutes, respectively. Ratings for Speaker 8 (Figure 3h) also plateaued after the palate was in place for 60 minutes, but his ratings were lower than preplacement levels. Four speakers reached preplacement ratings at least once while the EPG was in place.

Palatal fricatives (/ʃ/). Individual speaker ratings varied more for /ʃ/ than for /s/ and the conversation sample. The perceptual ratings for most speakers decreased, or remained low between 0 and 30 minutes following insertion of the EPG sensor (Figure 3a-h). Improvement took longer than for /s/ with six speakers making some improvements by 60 minutes. However, like for /s/, the ratings for these speakers decreased again at 90 and/or 120 minutes. The two exceptions were Speaker 2 (Figure 3b) whose ratings remained near preplacement levels for the last hour of wearing the device, and Speaker 6 speaker (Figure 3f) whose ratings gradually increased from 30 to 120 minutes of wearing the palate. Four speakers reached preplacement clarity at least once while the EPG was in place.

Except for Speaker 8 (Figure 3h), all speakers showed similar or near-similar trends for /s/ and /ʃ/. Three speakers (Figures 3b-d) demonstrated the same trend for /s/ and /ʃ/ at all time periods with /ʃ/ rated less clear than /s/. As seen in Figures 3e and 3f, Speakers 5 and 6 showed the same trend in ratings for /s/ and /ʃ/ except for 60 minutes postplacement. Speakers 1 and 7

(Figures 3a and 3g) showed similar trends for three of the five adaptation periods. All but two speakers showed generally lower listener ratings for /ʃ/ than for /s/. Listener ratings for speakers 2, 7, and 8 reached preplacement levels at least once for each sound.

Velar stops (/k/). Like /s/, most speakers showed improvement by 30 minutes postplacement for /k/; however, fewer reached preplacement speech clarity while the EPG was in place. For stimulus /k/, five speakers reached a plateau by 30 minutes postplacement; however, all speakers showed one reduction in listener ratings for one test at 60, 90 or 120 minutes. Speakers 2, 4 and 8 were the only speakers to near preplacement listener ratings with the EPG in place. As seen in Figures 3c and 3e, listener ratings for Speaker 3 and Speaker 5 began to increase gradually by 30 minutes postplacement, but neither achieved preplacement speech clarity with the EPG sensor in place.

Alveolar stops (/t/). As illustrated in Figures 3a-h, listener ratings for /t/ showed more speaker variability than the other stimulus types. Speakers 1 and 3 had similar trends with a decrease in speech clarity following placement of the EPG, and a gradual increase in clarity over time. While Speaker 3 reached near-normal clarity by 120 minutes, Speaker 1 did not. The trends in the ratings for the remaining speakers were inconsistent and distinct. Similar to /s/ and /ʃ/, four speakers reached preplacement levels at least once following placement of the EPG sensor, but none of them maintained preplacement speech clarity. For example, Speaker 4 (Figure 3d) had a preplacement rating of 94.0, he received a similar rating at 30 minutes (93.2) and 120 minutes (95.0), but not for the other time periods. On the other hand, Speaker 6, as shown in Figure 3f, increased in clarity from 82.5 preplacement to 87.7 following placement, and 95.7 after 30 minutes. He maintained this clarity until 120 when his score dropped to 60.7. Speaker 7 (Figure 3g) received a rating of 89.3 prior to insertion of the EPG, but the remainder of his scores—

including scores after the EPG was removed—were between 56.5 and 71.5. Despite the variability among speakers, listener ratings were concentrated above 50 for the test periods 90 and 120 minutes postplacement. Ratings were not concentrated above 50 while the EPG was in place for any other stimulus type. Six of the speakers showed similar trends for /k/ and /t/, for at least seven of the eight time periods. That is, the speakers generally followed the same trend for improvement or regression, but the magnitude of the change was different depending on the stimulus type.

Discussion

When collapsed over speaker and stimulus type, there was a significant difference in listener ratings before and after inserting the EPG sensor. Ratings also increased significantly after talking with sensor in place for 30 minutes, and again after talking with the sensor for an additional 30 minutes. No significant improvement in pronunciation was noted between the 60- and 120-minute test intervals. Overall, the speakers' pronunciation significantly improved after wearing the sensor for 30 minutes, and after 60 minutes; however, as a group their pronunciation did not reach preplacement levels until the sensor was removed.

When collapsed across stimulus type, individual speakers differed in how well they adapted to the EPG sensor; some speakers reached preplacement ratings with the EPG in place, while others did not. Additionally, adaptation patterns varied with some speakers showing improvement by 30 minutes and others by 60 minutes, with most speakers showing no additional improvement after wearing the sensor for 90 minutes.

Speakers showed mixed results in how they adapted across the different stimulus types. For the conversation sample, most speakers showed no improvement after 90 minutes following EPG placement, and only one speaker completely adapted to the EPG sensor. The speakers'

adaptation patterns were more variable across the different consonants compared to their performance in conversation. Ratings increased the most rapidly for /s/ and /k/ with improvement beginning after 30 minutes of wearing the sensor. Although ratings for /t/ did not improve as rapidly as they did for /s/ and /k/, they were higher than ratings for the other stimuli by the end of testing with the EPG in place. This indicates that participants approached full adaptation for /t/ more than for the other sounds.

The individual speaker differences observed in the current study are similar to those seen by Hamlet and Stone (1982). They observed that all participants made adjustments such as tongue retraction or advancement, groove narrowing, or jaw placement with initial placement of a dental retainer. Those who adapted to the retainer showed a change in articulator placement following the two-week period, indicating that they altered their articulator placement during the adaptation time. Those participants who did not adapt showed no change. In the current study, speakers differed in their adaptation patterns, regardless of the stimulus type. These individual differences may be the result of the same articulatory changes made by participants in the study by Hamlet and Stone.

Although Hamlet and Stone (1982) observed the effect of individual speaker differences on adaptation, several other adaptation studies of adults addressed differences across stimulus types. McFarland et al. (1996) found that stops showed no perceptual differences in speech immediately after placing the EPG sensor, or following a 15-minute conversation. Perceptual ratings for the fricative /s/ remained low following the conversation. Although listeners in the current study heard a decrease in quality of stops, the speakers' adaptation patterns for /t/ were generally better than for fricatives. The acoustic findings of a study by McAuliffe et al. (2007) are consistent with differences in perceptual clarity between /t/ and the fricatives /s/ and /ʃ/. In an

acoustic analysis, they found that the segment duration of consonants, and the frequency of vowel formants did not change with placement of the EPG sensor, while the EPG did change the first spectral moment for /s/.

Searl et al. (2006) used both an acoustic and a perceptual analysis to study the time needed for adult speakers to adapt their speech to a pseudopalate when producing the phonemes /t/ and /s/. Acoustic measures changed upon initial placement of the pseudopalate, but returned to normal by 30 minutes. For the perceptual analysis, listeners reported no differences in pronunciation of /t/ and /s/ following placement of the pseudopalate. This differs from the current study where listeners did report differences in speech clarity for both /t/ and /s/ following placement of the EPG sensor. One reason may be a difference in the scale provided to the listeners. The current study asked listeners to rate clarity; Searl et al. asked listeners to rate distortion. Additionally, adult speakers may adapt to the EPG more efficiently than children because adults have fully-developed speech, and because their mouth is proportionally larger as compared to the EPG sensor.

Although Searl et al. (2006) did not find that an adaptation period was necessary for speakers to reach preplacement speech production, a study by McAuliffe et al. (2007) found that adult speakers did need between 45 minutes and 3 hours to fully adapt their speech to the presence of the EPG sensor. Of note, ratings for the phoneme /s/ adapted the most quickly with a 50 percent increase in listener ratings between the initial placement of the sensor and 45 minutes postplacement, followed by a return to near-normal listener ratings by three hours of wearing the sensor. Similarly, in the current study, listener ratings of the children's speech pronunciation clarity increased by 30 minutes postplacement for the phoneme /s/; this is faster than they did for /t/ and /ʃ/.

In two previous graduate theses, Knapp (2014) and Celaya (2014) performed an acoustic analysis of the speech samples used in this study. Overall, they found that the duration was least affected by the presence of the EPG sensor. Similar to the current study, measures of intensity, showed a decrease after placement of the EPG followed by a gradual increase throughout the two hours, but intensity did not return to normal while the EPG was in place. Likewise, measures of spectral mean for /t/ and /ʃ/ showed a change with insertion of the EPG followed by general improvement. On the other hand, measures of spectral mean for /s/ and /k/ were inconsistent across speakers. Knapp and Celaya also observed that spectral variance was the most variable acoustic characteristics across speakers (Celaya, 2014) which is consistent with the individual variability observed in the current study.

Several limitations of this study should be addressed in future research. One was that a number of children gave short responses to the conversation prompts, while others' responses were more comprehensive. Speech rate also varied across speakers and test periods. In future studies, researchers could help children regulate their rate of speech across test periods by displaying the cue cards at a consistent rate, and by encouraging the children to use a pacing board. Additionally, researchers could maximize the length of the conversation by asking the children to talk for a certain amount of time, and minimize clinician interruption during the conversation. Another limitation is possible test fatigue which may have led the children to perform more poorly on the tests at 60, 90 and 120 minutes postplacement. Some of the speakers may have grown tired because of the length of the study, or because the EPG device was uncomfortable, or because of the repetitive nature of the test stimuli over the eight test intervals. To minimize the effects of test fatigue, researchers should consider shortening the overall test time, or the amount of stimuli. An incentive after each test, such as the opportunity to move on to

a new activity or earn a prize, would also motivate the children to increase their focus during each test.

Despite these limitations, findings of the current study provide insight into how children adapt to an EPG sensor and how their adaptation differs from that of adults. This information is particularly useful to clinicians who use EPG with their clients. When using EPG therapy, clinicians may benefit from knowing that individual differences can influence how quickly and completely a child adapts to an EPG sensor, and thus tailor treatment to each client. Additionally, adaptation across speakers and sounds is generally neither immediate, nor complete; as such, a client's speech productions will not sound like normal speech as long as the sensor is in place. As a result, clinicians may want to give children the opportunity to practice speech sounds following EPG treatment. Doing so will increase the effectiveness of EPG treatment by allowing children to generalize what they learned during EPG therapy to their everyday speech.

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APPENDIX A: Annotated Bibliography

Cheng, H. Y., Murdoch, B. E., Goozee, J. V., & Scott, D. (2007). Electropalatographic assessment of tongue-to-palate contact patterns and variability in children, adolescents, and adults. *Journal of Speech, Language, and Hearing Research, 50,* 375-392. doi:1092-4388/07/5002-0375

Objective: To show how tongue-to-palate contact patterns develop from childhood to adulthood. *Method:* Forty-eight participants from six years to adult were involved in this study. Participants were divided into four groups according to age with six males and six females in each group. Prior to testing, each participant wore the EPG device until their speech was normal as determined perceptually by the examiner. Participants then repeated words with the following sounds in the initial position: /t/, /s/, /k/, /l/, /kl/, and /st/. Acoustic and EPG data were collected and analyzed for each speaker. *Results:* Overall representative frames of maximum contact for the phonemes /t/, /l/, and /s/ showed that the areas of most tongue-to-palate contact for each age group moved more anteriorly as the age of the group increased. Additionally, the older groups had more consistent contact patterns across speakers, and made contact with fewer electrodes for each sound. Overall representative frames of maximum contact for /k/ were about the same for all age groups. The position of the tongue on the palate for /k/ in the younger speakers was more posterior and the tongue showed complete closure on fewer rows, with less midline contact. When collapsed over age and sound, females showed less contact overall, but these results were not consistent. *Conclusion:* As children mature into adulthood, the tongue-to-palate contact decreases, and the place of articulation moves forward in the mouth for consonants like /t/, /s/, and /l/, and some consonants stabilized as the children grew older. This indicates that children continue to develop their articulation into adulthood. *Relevance to Current Study:* Researchers must consider differences between the articulation of children and adults as they apply methods previously used to only with adults to study children.

Dromey, C., Nissen, S., Nohr, P., & Fletcher, S. G. (2006). Measuring tongue movements during speech: Adaptation of a magnetic jaw-tracking system. *Speech Communication, 48,* 463-473. doi:10.1016/j.specom.2005.05.003

Objective: The purpose of this study was to determine if a system that typically uses magnetic pellets to track jaw movement can be adapted to effectively track the tongue during speech. *Method:* The authors used an adapted version of the JT-3 jaw-tracking device made by BioResearch Associates. Adaptations included a smaller magnetic piece that would fit on the tongue; and the ability to control the type and frequency of recorded data. The authors studied many functions of the device; however, most relevant is the effect of the presence of the lingual magnet on speech. Five English speakers said words containing /s/ and /ʃ/ in the initial, medial, and final positions in the carrier phrase, "I say the word ___ again." The authors compared characteristics of duration and spectral mean for sounds produced with and without the magnet. *Results:* Results of the speech analysis showed no significant difference between the fricatives produced with or without the magnet. *Conclusion:* The magnet did not disrupt fricative production. *Relevance to current study:* Devices involving magnetic sensors do not require the same adaptation time as EPG devices.

Fletcher, S. G. (1989). Palatometric specification of stop, affricate and sibilant sounds. *Journal of Speech and Hearing Research, 32*, 736-748. doi:10.1044/jshr.3204.736

Objective: To study how children make stop, affricate, and sibilant sounds. *Method:* Nine children ages 6.8 to 14.8 were fitted with a 0.5 mm EPG sensor. Stops /t/, /d/, /k/, and /g/, sibilants /s/, /z/, and /ʃ/, and affricates /tʃ/ and /dʒ/ were combined with the vowels /i/ and /ɑ/. After a twenty-minute adjustment period, the participants were asked to said each CV combination and to open their mouth wide between each word. Each participant was tested five times separated by short, three- to five-minute breaks. Each sound was separated into three segments: rising tongue-to-palate contact (segment 1), consonant production (segment 2), and vowel production (segment 3). *Results:* Some of the primary results for sibilants, showed the tongue-to-palate contact was highest in the middle of the sibilant. Contact decreased before the following vowel and stopped decreasing as soon as the vowel was reached. Thus, there was more tongue-to-palate contact for /i/ than for /ɑ/. Affricates, on the other hand, had a plateau in tongue-to-palate contact in the middle of

the sound. The length of the plateau was equal to the length of time between the peak contact and noise burst in sibilants. Additionally, more sensors were contacted fo affricates than fo sibilants. A study of /ʃ/ as a phoneme and as a portion of the affricate /tʃ/ showed that both forms of /ʃ/ had similar contact patterns. Also notable was that affricates and stops had different vowel onset times. In relation to the other phonemes tested, the authors found that /s/ and /z/ were formed with a groove that was narrower and more anterior than the grooves in ʃ and the fricative portions of tʃ and dʒ. Analysis of age differences showed that older speakers formed phonemes faster and with more precision than the younger participants. *Conclusions:* From these results, the author concluded that the plateau in the affricate is the point where the sound changes from a stop to an affricate. Additionally, stops and affricates are indeed two different classes of consonants with the affricate requiring more skill and effort from the speaker. Finally, as children develop, they are able to form speech more efficiently and precisely. *Relevance to Current Study:* This study is valuable in that it studies EPG use in children. The patterns found will be important for the current researcher to consider when selecting sounds and comparing results of children of different ages.

Fletcher, G. S., McCutcheon, M. J., & Wolf, M. B. (1975). Research note: Dynamic palatometry. *Journal of Speech and Hearing Research, 18*, 812-819. doi:10.1044/jshr.1804.812

Objective: A research note describing an electropalatometer. *Method:* The palatometer is made of the pseudopalate and 48 electrodes. The design of the pseudopalate is two plastic sheets with the wiring for the electrodes in between. The wires protrude through holes on the inferior sheet so they can contact the tongue. When the tongue contacts the palate, it creates a circuit from a 100 mv charge on the client's wrist. This analog signal travels out of the wires and is converted to digital information and then projected on a light emitting diode (LED) display. The patterns from the electrodes could be recorded on magnetic tape and then reviewed in conjunction with an acoustic spectrum, or as a summary of the data across repeated syllables. Such a summary can help account for the variance in repetitions of the same syllable. *Conclusions:* The palatometer can help measure tongue-to-palate contact during speech, and provide researchers with a way to analyze articulation through digital recordings and displays of palatometer measures. *Relevance*

to current study: This research note describes the design and function of the electropalatometer, the device that will be used to gather data in the current study.

Gay, T., Lindblom, B., & Lubker, J. (1981). Production of bite-block vowels: Acoustic equivalence by selective compensation. *Journal of the Acoustical Society of America, 69,* 802-810. doi: 10.1121/1.385591

Objective: To study articulator position and acoustical characteristics of vowels with and without a bite block, and to determine if adaptation to the bite block is a neurophysiological phenomenon. *Method:* Five males said a series of Swedish vowels with and without a bite block in place. A 22.5 mm bite block was used for vowels that are produced with a small mouth opening, and a smaller, 2.5 mm bite block for vowels that are naturally more open. Each speaker repeated the vowel nine times and held the last repetition. While the speaker held the vowel, the experimenters took an x-ray from the side of the person's face. These images were traced to show important structures for articulation, and then digitally analyzed for cross-dimensions. The experimenters also used a computer simulator to test how changes in articulator placement would affect the acoustic characteristics of the vowel. *Results:* X-ray analysis showed that when a bite block was in place, the articulators would compensate, or *super shape* to reach normal speech placement. Articulators came closest to normal-speech positioning in areas that were most constricted for that particular sound; more variation was seen in the more open areas of the vocal tract. The simulations showed that areas of high constriction are the most important in making a phoneme sound normal when a bite block is in place. *Conclusion:* Vowel formation is a neurophysiological phenomenon in which vowel formation is coded according the most important locations for an acoustically-sound production (i.e., high constriction points). *Relevance to Current Study:* The results of this study could possibly apply to an EPG device as well. That is, tongue positioning as recorded on the EPG system may most closely resemble speech in areas of highest constriction.

Gibbon, F. E., & Paterson, L. (2006). A survey of speech and language therapists' views on electropalatography therapy outcomes in Scotland. *Child Language Teaching and Therapy, 22,* 275-292.

> *Objective*: To learn about clients who participated in EPG therapy between 1993 and 2003, their therapy, and their progress as reported by their speech therapists. *Methods:* The authors surveyed ten speech-language therapists in Scotland. Therapists were asked to provide information on clients who received therapy with an EPG device. This information included demographics, type of disorder, therapy given, and effect of EPG therapy on progress. *Results:* The phoneme /s/ was treated the most in EPG therapy. Students with functional disorders appeared to benefit least from EPG therapy, while clients with cleft-palate seemed to benefit the most. Results also showed that 88% of the clients had trouble generalizing skills learned in therapy. This indicates that EPG therapy was most effective in establishing proper speech sound production, but not in generalizing or maintaining these productions outside the clinic. *Conclusions:* This study shows a need for further research in increasing generalization and maintenance in EPG therapy. *Relevance to Current Study:* This article shows that EPG is effective in teaching proper speech sound formation. This provides a need for research on how children adapt to an EPG device to help therapists most effectively use EPG systems to help children in therapy.

Hamlet, S. L., & Stone, M. (1982). Speech adaptation to dental prosthesis: The former lisper. *The Journal of Prosthetic Dentistry, 47*, 564-478. doi:10.1016/0022-3913(82)90311-0

> *Objective:* To determine if a history of lisping is related to difficulty adapting to a dental retainer. *Method:* Participants were 13 college students who reported lisping on /s/ as children, but now had normal speech. They were each given a dental prosthesies and asked to wear it for two weeks. Data were before and after the two-week period to measure jaw movement and tongue placement. In the initial measurements, speakers read target sentences first with a 1mm electropalatography (EPG) device to measure near-normal speech. Then participants read the sentences with an EPG the same size as the dental prosthesis. Data for this study focused on tongue contact for initial /s/ and /z/, and jaw height for initial /s/ and /z/ as well as /t/, /d/, /n/, and /l/. Following the two-week

adaptation period, participants rated how well they felt their speech had adapted to the device. *Results:* Seven of the participants reported that they had adapted to the speech device within the two-week period. The other six reported that they still felt the device obstructed their speech, or that listeners noted a difference in their articulation. Both participants who adapted and participants who did not adapt showed differences in place of articulation as compared to an earlier study of normal speakers. Nonadapters made adjustments such as tongue retraction or advancement, groove narrowing, and jaw placement with initial placement of the prosthesis, and maintained these same adjustment throughout the two-week period. However, participants who adapted to the device, showed a change in their articulation adjustments between the initial and final tests. *Conclusion:* People with a history of lisping use changes in tongue-palate placement (i.e., retracting and advancing) to adjust to the dental prosthesis more than people without a history of lisping. Additionally, participants who were able to adapt to the dental prosthesis, used different compensatory behaviors than those who did not. *Relevance to current study:* The results of this study should be taken into account when assessing adaptation in the present study. Researchers should be aware that adaptation time could be longer for children with a history of lisping. Additionally, variation among speakers may occur as a results of speakers' different adaptation behaviors.

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

Objective: To determine which acoustic cues relate best to place of articulation; then to describe the characteristics of these cues and their location within a sound. *Method:* Twenty participants said the consonants /f/, /v/, /θ/, /ð/, /s/, /z/, /ʃ/, and /ʒ/ in consonant-vowel-consonant (CVC) combinations. Their productions were recorded and the examiners analyzed spectral properties, transition information, and noise duration for each of the productions. All of the results from this analysis were used as predictors in a discriminant analysis to determine which acoustic measures best predicted the place of articulation for the fricatives. *Results:* Spectral peak location, normalized amplitude, and relative amplitude were the best cues for place of articulation across all of the fricatives. *Conclusion:* All four places of articulation for fricatives can be identified through

acoustical analysis regardless of voicing, surrounding vowels, and differences in production. *Relevance to Current Study:* Characteristics of fricatives in normal speech can serve as indicators of adaptation when speakers are tested while wearing an EPG device.

Mantie-Kozlowski, A., & Pitt, K. (2014). Treating myofunctional disorders: A multiple-baseline study of a new treatment using electropalatography. *American Journal of Speech-Language Pathology, 23*, 520-529. doi:10.1044/2014_AJSLP-14-0001

Objective: To determine if electropalatography (EPG) can be used to improve swallowing patterns in people with non-speech orofacial myofunctional disorders (NSOMD). *Method:* Three clients with NSOMD were selected for this study. This was a multiple-baseline study in which baseline and follow-up measures consisted of recording a series of saliva swallows on the EPG system. Each participant wore the EPG palate for a 30-minute adaptation time prior to each testing session. Tongue-to-palate contact patterns for each of the four stages of swallowing (pre-propulsion, propulsion, post-propulsion, and release), were analyzed for average duration and how often the participant's performance matched peers who do not have NSOMD. Treatment goals were set based on the baseline data. Treatment was held twice a week for 30-minute sessions and included biofeedback and clinician modeling with the EPG system. Participants were re-tested in a follow-up test five to eight weeks after treatment ended. *Results:* Two of the three participants reached all of their treatment goals for the intervention. Follow-up testing showed that two of the three participants performed above baseline, indicating that the effect of intervention remained after five to eight weeks. *Conclusions:* This study shows that EPG can be a valuable tool in helping people with NSOMD develop better tongue-to-palate contact and lingual control in swallowing. *Relevance to Current Study:* A particularly relevant part of this article is that the experimenters allowed an adaptation time before testing the participants' swallow. Additionally, results from the current study may be expanded beyond articulation therapy.

McAuliffe, M. J., & Cornwell, P. L. (2008). Intervention for lateral /s/ using electropalatography (EPG) biofeedback and an intensive motor learning approach: A case report. *International Journal of Language and Communication Disorders 43*, 219-229. doi: 0.1080/13682820701344078

Objective: To evaluate the adaptation time needed before an EPG device can be used for therapy or data collection. *Method*: Participants for this study were eight female college students. Participants were fitted with a 1-2 mm practice palate—an EPG without electrodes. Participants used the phrase *a [CVC]* as a context to test the consonants /t/, /k/, /s/, and /ʃ/ with the vowels /i/, /a/, and /u/. They said each word five times in each of four testing sessions: (1) before using the palate, (2) immediately after inserting the palate, (3) 45 minutes post-insertion, and (4) three hours post-insertion. Seven female college students rated the intelligibility of the initial consonant in the third repetition of each target word. The data were acoustically analyzed for the segment duration, first and second formant frequencies, and consonant spectra. *Results:* The perceptual analysis showed an increase in the judges' rating of imprecision between the test immediately before and after placement. However, ratings decreased significantly (indicating more precision) between the tests 45 minutes and three hours following palate placement. Of note, the phoneme /s/ adapted the most quickly as manifest by an approximately 50 percent decrease in ratings between the second and third test intervals, and a return to near-normal precision by three hours following placement. Most phonemes to showed no significant difference in segment duration for any of the test sessions. No differences in vowel formant frequencies across the test sessions were found. For analysis of the first spectral moment (mean: M1), /k/ had a significantly higher M1 three hours postplacement as compared to the normal speech conditions. Additionally, M1 for /s/ was lower for the three tests following placement of the practice palate. *Conclusions:* The results of this study indicate that initial imprecision can be detected immediately after insertion of the pseudopalate; however, adaptation typically occurs within 45 minutes to three hours postplacement. Additionally, acoustic measures showed that the segment duration of consonants and the frequency of vowel formants are not significantly affected by an EPG palate. *Relevance to current study:* This study employs similar methods to those that will be used in this thesis. These methods include testing consonant phrases at increments following the placement of an EPG device.

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

Objective: To study the amount of compensation speakers made when speaking with a bite block in their mouth, and to determine the effect of auditory and sensory feedback on that compensation. *Method:* The participants in this study were 15 French-speaking women. They were asked to say the vowels /i/, /a/, and /u/ in isolation and following the consonants /p/, /t/, /k/, /s/, and /ʃ/. During each test, each stimulus sound was presented 10 times in a random order. The study included two subtests. First, the immediate subtest which tested each participants' normal speech and speech with a small bite block (2.5 mm for vowels and 5 mm for consonants) and a large bite block (22.5 mm for vowels and 10 mm for consonants). The second test was the post-conversation subtest in which the speaker spoke for 15 minutes while wearing a 10 mm bite block before saying the test stimuli. Recordings of the tests were analyzed for sound duration, vowel formant frequency, and consonant centroid frequency. *Results:* There was no significant difference for the duration of vowels or stops in the bite block condition as compared to the normal speech condition; however, the bite block did affect the length of fricative production. Spectral analysis showed that for vowels, F1 was highest in the large bite block (LBB) condition. F2 frequencies differed, being higher in the LBB condition for /u/, but lower for /i/. During consonant production, speakers' centroid frequency was the lowest in the LBB condition compared to the normal and small bite block (SBB) condition. Fricatives had lower centroid frequency for both SBB and LBB tests. In post conversation testing, the formant frequency and duration of vowels was not significantly different from the normal-speaking condition. However, in consonant production, significant differences were found between the post-conversation bite block condition, and the normal-speaking condition. *Conclusions:* For vowels, speakers can learn to compensate for the bite block as they use it longer. This may be a result of auditory feedback that allows the speaker to correct for errors. Consonants, on the other hand, require a much longer adaption time if the speaker is to adapt at all. *Relevance to Current Study:* This study shows that an obstruction in the oral cavity can affect speech and that speakers require adaptation time to compensate for the obstruction.

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

Objective: To study the way in which speakers adapted to thick and thin pseudopalates and to compare results to a previous study done with bite blocks. *Method:* Fifteen, French-speaking women participated in this study. Each participant was fitted with a thick (6 mm) and thin (3 mm) pseudopalate. Participants took part in two subtests. The first was the immediate compensation subtest where speakers were tested with no palate, and both the thin and thick palates. The second subtest was the post-conversation subtest where speakers spoke for 15 minutes while wearing the thick pseudopalate before being tested. Test stimuli included the vowels /i/, /a/, and /u/ in isolation, and these vowels following the consonants /p/, /t/, /k/, /s/, and /ʃ/. Participants said each stimulus item five times for each test condition. Recordings were analyzed for consonant and vowel duration, first and second vowel formant frequency and consonant centroid, skewness and kurtosis. Vowel and consonant sounds were isolated for perceptual analysis in which judges selected the sound from several choices, and rated its quality. *Results:* Vowels did not differ acoustically or perceptually between tests done with or without the palate. Centroid, skewness, and kurtosis measures were lower with the palate than without the palate for /s/. Identification and quality ratings were lower for the fricatives in the immediate compensation subtest with the palate. However, in the post-conversation test, only quality was rated lower. Stops showed some acoustic differences between palate, and no-palate conditions during both subtests; in the immediate compensation subtests, differences only occurred between the palate and no-palate conditions. No differences were measured in perception ratings for consonants. *Conclusion:* First, vowels are the least affected by a pseudo palate, followed by stops, and then fricatives. Second, the subtle changes required by a thin palate may be more difficult for the mouth to immediately adjust to than the large changes caused by the thick palate. Third, adaptation can occur over time for some phonemes as a result of sensory feedback. Finally, people adapt to pseudopalates differently than bite blocks. *Relevance to Current Study:* This study supports the idea that people can adapt to an EPG palate over time. Additionally,

the current authors should keep in mind that this compensation may not occur in the same way for all phonemes.

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

Objective: To study adaptation to an EPG in relation to acoustical and perceptual data, as well as participant report. *Method:* Seven Australian adults were the subjects for this study. Each was fitted with an EPG and pseudo-EPG device. Testing consisted of 15 trials over two days. In each test, the participant said the phrases [ə ti], and [ə si], counted to 20, and read "The Rainbow Passage." Acoustic measures were taken for the two phrases. A speech-language pathologist listened to the recordings of the participants counting and reading the passage. She was asked to record whether or not she thought the speaker was wearing the palate, and then rate the naturalness and distortion of the participant's speech. Participants were periodically asked to rate the effect of the palate on five areas: comfort, speech, tongue movement, sensation in mouth, and appearance. *Results:* Both the EPG and pseudo-EPG palates affected speech. General adaptation occurred for /t/ after about one hour, and /s/ after two hours; however, no speaker produced speech that acoustically matched the no-palate condition. Adaptation did not continue if the palate was removed and then reinserted. Overall, the palate had only a small effect on perceptual distortion ratings with affricates and fricatives being most notably affected. Participants indicated that the palate significantly affected the five areas listed above. Some also indicated that the palate changed the sensation in their mouths even after the palate was removed. *Conclusions:* Typical adults showed some ability to adapt to an EPG device. The EPG did not grossly affect the perceptual characteristics of speech. *Relevance to Current Study:* This study suggests an adaptation period of one to two hours; results from the current thesis can be compared to this time. Additionally, the participant's perspective on wearing the EPG will help the current authors to anticipate possible problems and discomforts the participants might experience during this study.

Nissen, S. L., & Fox, R. A. (2009). Acoustic and spectral characteristics of young children's fricative production. *Journal of the Acoustical Society of America, 126*, 1369-1378. doi: 10.1121/1.3192350

Objective: This study analyzed the acoustic characteristics of the production of /p/, /t/, and /k/ by children ages three to five, and adults. The study also discussed how the age and gender of the speaker, place of articulation, and vowel context affected the amplitude and spectral properties of the phonemes /p/, /t/, and /k/. *Method:* The experimenters studied four groups of ten participants: (1) children age 3;0 to 3;11 years, (2) children age 4;0 to 4;11 years, (3) children age 5;0 to 5;11 years, and (4) adults. Participants were asked to say several words in a carrier phrase, "This is a ___ again." These words contained one of the target consonants (/p/, /t/, or /k/) in the initial position, followed by a vowel. The examiner elicited the target words by having the participant name pictures of each of the items. These responses were recorded. To analyze the samples, the experimenters first isolated the onset and offset portions of the target consonants. They then calculated the normalized amplitude for each stop burst, and conducted a spectral moments analysis to find the spectral mean, variance, skewness and kurtosis. A statistical analysis was performed to detect differences resulting from the age and gender of the speaker, place of articulation, and vowel context. *Results:* For the analysis of normalized amplitude, the authors found differences in normalized amplitude for the three different places of articulation, and the three vowel contexts. Spectral measures included spectral slope, mean, variance, skewness and kurtosis. For spectral slope measures, the experiemnters found different slope values for all of the target consonants in each of the three vowel contexts; the vowel /i/ particularly elevated the slope for a preceding /k/ or /t/. Additionally male speakers in the 5-year old and adult groups had lower spectral slope than the females. The analysis of spectral mean found a difference among the three places of articulation. The vowel /i/ also increased the spectral mean for /k/, but not significantly for /p/ and /t/. Overall, the female and child participants produced a higher mean than the adult males. Differences in spectral mean by gender were shown for /p/ and /t/ in participants four years old and older, and for /k/ in the five-year-old and adult groups. Generally, the mean for /t/ and /k/ was lower in males. The spectral variance for /p/ was found to be higher than for /t/ and /k/. Additionally, the vowel /i/ lowered the spectral

variance for /p/ and /k/, and raised it for /t/. Measures of spectral skewness found that the skewness for the target consonants differed from each other. When /i/ followed the consonant /t/, the skewness of the stop was lowered. Gender differences in spectral skewness were found starting at age 5. The spectral kurtosis measurements were different for /p/, /t/, and /k/, and the measures increased as the place of articulation occurred farther back in the mouth. *Conclusions:* This study found that the place of articulation changes the spectral measures for different consonants. This is particularly true for spectral variance that can help separate /p/ from /t/ and /k/ in an acoustic analysis. Secondly, this study showed that the vowel following a consonant affected the spectral measures of that consonant. Additionally, the effect of vowel context on the normalized amplitude of the preceding consonant provides support for the idea that the acoustical properties of vowel affect the perception of a preceding consonant. As for the effects of age and gender on articulation, this study suggests that gender differences in articulation are the result of learned articulatory patterns, not the vocal mechanism. *Relevance to Current Study:* The current study uses only one vowel context with the target phonemes. According to this article, the vowel context may change the patterns seen in speakers' adaption to the EPG sensor.

Searl, J., Evitts, P., & Davis, W. J. (2006). Perceptual and acoustic evidence of speaker adaptation to a thin pseudopalate. *Logopedics Phoniatrics Vocology, 31*, 107-116. doi: 10.1080/14015430500390961

Objective: This study used acoustic and perceptual measures to study the effect of a thin (0.5 mm) pseudo palate on adult production of the phonemes /t/ and /s/. *Method:* Eleven adults (five male and six female) participated in the study. Each participant was fitted with a custom pseudopalate that was 0.5 mm thick in all areas. The target phonemes /t/ and /s/ were tested by having the participants say /tik/ and /sik/ five times using the carrier phrase *a ___ again*. These repetitions were spoken in a random order as prompted by slides on a computer screen. Participants performed this task at nine different intervals during the tests: before wearing the pseudopalate; directly after inserting the palate; at 15 minute intervals up to 60 minutes following placement of the pseudopalate; after two hours of wearing the palate; after removing the palate; and 15 minutes after removal. Participants did not talk between tests. Each test was recorded and acoustically analyzed.

Additionally, 10 experienced speech-language pathologists listened to the recordings and performed a perceptual analysis. Participant results for the acoustic analysis and the perceptual analysis were combined for each of the nine testing stages and a statistical analysis was done for each. *Results*: The tests had three main findings. First, as manifest by the following acoustic measures, the production of the target phonemes had acoustic changes in the participant's speech shortly after inserting the pseudopalate. For measures of spectral moment 1 (SM1), the experimenters noted that SM1 for /t/ was higher 15 minutes after wearing the pseudopalate than for all other tests. For /s/, SM1 was higher immediately after placement, and 15 and 30 minutes after placement. The stop-gap duration was higher immediately after inserting the pseudopalate, and after 15 minutes of wearing it. Differences in fricative duration, however, were not statistically significant. Secondly, although these differences were observed in acoustic measures, they were not manifest in the perceptual measures. Listeners identified the target phoneme with at least 98 percent accuracy for every test, and mean distortion ratings were between one and six percent. The third finding was that speakers adapted to their pseudopalate in about 30 minutes after placement. This is manifest by the acoustic measures returning to preplacement levels. *Conclusion:* Little or no adaptation time is needed for people to produce perceptually undistorted consonants with a 0.5 mm pseudopalate. Acoustically accurate productions occur after the participant has worn the pseudopalate for about 30 minutes. *Relevance to Current Study:* This study tests consonant phrases at increments following the placement and removal of an EPG device, much like the methods used in the current thesis.

APPENDIX B: Consent Form

Informed Consent Document

Consent to be a Research Participant (Adult listener)

Introduction
The purpose of this study will be to analyze how younger speakers, eight to ten years of age, adapt their obstruent sound productions when a relatively thin sensor is placed in their mouth. This experiment is being conducted under the supervision of Shawn Nissen, Ph.D., an associate professor in the Department of Communication Disorders at Brigham Young University. You have been invited to participate because you are a native English speaker with no known history of a speech, language or hearing problems.

Procedures
Participation in this study will involve one visit of approximately thirty minutes, which will take place in a research laboratory in the John Taylor Building at BYU. You will be asked to listen to individual sounds, words, or sentences spoken by children and respond regarding your perception of the intelligibility and pronunciation of their speech.

Risks/Discomforts
There are minimal risks for participation in this study.

Benefits
There are no direct benefits to participants. However, it is hoped this study will provide understanding that may assist clinicians and researchers in developing more effective approaches to assess and treat communication disorders.

Confidentiality
All information provided will remain confidential and will be reported only as group data with no identifying information. All data, including records of your listening responses, will be kept on password-protected computers in a locked laboratory and only those directly involved with the research will have access to them.

Compensation
You will be compensated $15 per hour for your participation in this study.

Participation
Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate without penalty.

Questions about the Research
If you have questions regarding this study, you may contact Shawn Nissen, Ph.D., at (801) 422-5056 or shawn_nissen@byu.edu.

Questions about your Rights as Research Participants
If you have questions regarding your rights as a research participant, you may contact the BYU IRB Administrator, A-285 ASB, Brigham Young University, Provo, UT, 84602 or at (801) 422-1461.

I have read and fully understand the consent form. Any questions have been answered to my satisfaction. I give my consent to participate in this research.

Signature:_____   Date:_____

Printed Name: _____

Institutional Review Board	
2-9-2016 Approved	2-8-2017 Expires