To the Graduate Council.

I am submitting herewith a thesis written by Amy Elizabeth Carrubba entitled "A comparison of two methods of formant frequency estimation for high-pitched voices." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Speech Pathology

Mary L Erickson Ph D., Major Professor

We have read this thesis
And recommend its acceptance.

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

A COMPARISON OF TWO METHODS OF FORMANT FREQUENCY ESTIMATION FOR HIGH-PITCHED VOICES

A Thesis

Presented for the

Master of Arts Degree

The University of Tennessee, Knoxville

Amy Elizabeth Carrubba

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While I sit in front of this computer for one last night, I stare silently at the screen through tears of both joy and sadness I reflect on my graduate school career with an overwhelming feeling in my heart as I realize that, never in my life have I learned, loved, or accomplished so much as I have over the past two years. I have grown academically, spiritually and emotionally and would love to express my gratitude to the people who have contributed part of themselves to me to make this happen.

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ABSTRACT

Formant frequency estimation is necessary when studying the vocal apparatus non-invasively. It is almost impossible to accurately measure formant frequencies in high-pitched voices due to the wide spacing of harmonics.

This study sought to test the accuracy of two methods of formant frequency estimation: artificial laryngeal stimulation via neck placement and via oral tube insertion. Twenty males between the ages of 18 and 45 performed the following three tasks: (1) four seconds of sustained vowel, (2) two seconds of sustained vowel followed by two seconds of artificial laryngeal stimulation via neck placement while ceasing vocal fold vibration and holding structures of the vocal fold filter in a fixed position, and (3) four seconds of sustained vowel, the last two of which were accompanied by artificial laryngeal stimulation via an oral insertion. These task were performed on the vowels /ɑ/ and /i/. Four formant frequencies were measured for each task at second one and second three. These measures were compared across second one and second three, as well as across all three tasks. Group means as well as individual subject analysis were compared.

Formant frequency estimation via artificial laryngeal stimulation with oral tube insertion appeared to be the more accurate of the two methods when comparing group means However, the individual analyses revealed that neither of the two methods was an accurate predictor of formant frequencies. This was most likely due to movements of the structures contained in the voice filter.

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CHAPTER ONE

OVERVIEW OF STUDY

INTRODUCTION

Once upon a time in a far away land there was a field of science considered so important that those who were ignorant of its content were considered to be uneducated. The time was the year 380 BC, the land was Greece, and the science was music (Grout, 1973). By the middle ages, music was no longer considered a science, but instead had developed into a form of art. Today, for most people, music is entertainment. For others, it is a form of art. Yet for a small group of people, it has again become a science.

During the 1900's, researchers began investigating the acoustic properties of musical instruments. Yet it was not until the second half of this century that scientists turned their attention to the study of the singing voice. The field of singing voice science can be said to originate with the publication of Vennard's classic "Singing: The mechanism and the technique" in 1967. As we approach the second millennium, however, many questions concerning the production and acoustics of the singing voice remain unanswered.

Because the vocal instrument is largely hidden from view, information concerning its function is often obtained through acoustic analysis. According to the source-filter theory (Fant, 1970), the voice is a linear system where vocal output is a product of the voice source (the vocal folds) and the filter (the vocal tract). The acoustic characteristics of the filter provide information about vocal tract shape and size, while the acoustic characteristics of vocal fold vibration provide information about vocal fold physiology. Unfortunately, neither of these can be obtained easily in the singing voice. This is due to the wide spacing of harmonics produced in high-pitched vocal productions The difficulty arises when men sing in the upper part of their range, when women sing in the middle and upper parts of their range, and also when children speak in normal voice.

Several methods for estimating formant frequencies in high-pitched voices have been proposed and even utilized in research, but none have been tested for accuracy. This study seeks to test the accuracy of two methods of formant frequency estimation. It is hoped that at the conclusion of this study, with the dawn of the new millennium, in a land not-so-far way, the acoustic monster will be defeated and important information about the acoustics of the singing voice will live happily ever after.

REVIEW OF THE LITERATURE

Acoustic Analysis of Speech Sounds

Source Filter Theory

According to the source-filter theory (Fant, 1970), output speech can be represented by a linear model, p(f) = s(f) t(f) r(f), where s(f) represents the acoustic output of the vibrating vocal folds, t(f) represents the filtering effect of the vocal tract, and r(f) represents the effect of lip radiation. The term phonation can be correlated with the term source, just as articulation relates to filter. In a purely linear model, the filter function is independent of the source Hence, the generation of sound is considered to be a separate parameter from the articulatory shaping of its phonetic quality.

While there is some evidence that, at least in situations such as high-pitched female singing, phonation may not truly be independent of articulation (Hertegard & Gauffin, 1994), scientists and researchers can still learn a great deal about phonation and articulation by determining the true resonance characteristics of the vocal tract and the true spectrum of the source This requires an accurate determination of the frequencies and bandwidths of the formants so that their effects on the output spectrum may be removed.

Interpretation of Filter Information

Scientists cannot understand the contribution of the filter to speech production without accurate measurement of formant frequencies and bandwidths. Formant frequencies are directly related to articulation and provide information vital to vowel perception. Formant frequency patterns also provide acoustic cues related to the perception of vocal quality and timbre.

Vowel Production and Perception

Tongue advancement and height play a significant role in the perception of vowels in English (Rakerd and Verbrugge, 1985). The frequency of the first formant (F1) varies inversely with tongue height for a given vowel. For example, /i/, which is a high vowel, would have a low first formant. The second formant (F2), however, varies with tongue advancement. Front vowels have a high second formant where as back vowels have a low second formant (Kent & Read, 1992).

In 1952, Peterson and Barney conducted an investigation involving 76 speakers (33 men, 28 women, and 15 children) and 70 listeners. They compared the relationships between a listener's vowel identification to its properties as revealed from acoustic measurement. The speakers produced a list of ten monosyllabic words in (hVd) context Those words were presented to the 70 listeners for vowel identification. In addition, the following acoustic measurements were obtained through narrowband spectra: formant frequencies, formant amplitudes, and fundamental frequencies. The results for accurate identification were as follows /i/ = 94 %, /I/ = 49 %, and /E/ = 34 %. It was noted that when speakers disagreed on vowel identification, the intended and perceived vowels were almost always in adjacent positions on the vowel loop, a plot where the frequency of F1 is plotted as a function of the frequency of F2. Peterson and Barney showed a strong relationship between the intended vowel and the formant frequency pattern.

<u>Perception of Voice Quality</u>

As observed by Peterson & Barney (1952), formant frequencies are higher in children than in adults Within the adult population, women's formant frequencies tend to be higher than men's. This is not surprising, since perturbation theory (Kent & Read, 1992) predicts that formant frequencies are directly related to vocal tract length. The longer the length, the lower the formant frequency (Fant, 1970). The distance in relative frequency between formants is also related to the length of the vocal tract. Females have larger average formant spacings than males. Again, this is due to their shorter vocal tract length.

There are differences in formants between different classes of speakers and singers. The most influential factors in classifying different voice types have been shown to be formant frequency and pitch differences (Cleveland, 1977). The formation of high and low singing formants, as well as the timbre characteristics of a particular voice type are both directly correlated with the dimensions of the bucco-pharyngeal tract. A fixed length of the vocal tract has been shown to decrease with each voice class as follows: bass, baritone, tenor, mezzo-soprano, and soprano (Dmitriev and Kiselev, 1979).

Interpretation of Source Information

The acoustic and aerodynamic characteristics of the vocal fold vibration can provide valuable information concerning their structure and function. The slope of the source spectrum provides valuable information concerning the degree of adduction of the vocal folds while numerous parameters associated with the glottal volume velocity waveform provide information about adduction and potential pathology.

The acoustic signal derived from inverse filtering can be transformed into a spectrum through a Fourier transform. The glottal source spectrum can in turn give us information about the voice source. For example, it can provide us with information about the quality of a person's voice. In a normal speaking voice, the harmonics in the voice spectrum will drop off by 12 dB per octave. A voice spectrum with a steeper slope, usually is indicative of a breathy voice. If the slope is shallow, however, tightly adducted vocal folds are likely.

Likewise, the airflow signal derived from inverse filtering of the glottal volume velocity waveform provides us with important information. The open phase and the closed phase of the waveform estimate the amount of abduction and adduction, respectively, of the vocal folds. The maximum flow declination rate, which is the point on the waveform with the steepest negative slope, tells how fast the vocal folds are closing. The faster the closing rate, the more energy there will be in the high harmonics. Another characteristic is the direct current (DC) offset. This is a constant airflow that occurs even when the vocal folds are maximally adducted. A large DC offset indicates an incomplete glottal closure, suggesting weak adduction or pathology.

The acoustic and aerodynamic characteristics of the vocal folds can be obtained through inverse filtering, a process by which vocal tract resonances are removed from either the acoustic or the airflow signal radiated from the lips (Colton & Casper, 1996)

Methods of Formant Estimation

Currently, several methods are available for measurement of formant frequencies Each of the methods have both positive and negative aspects

Spectrography

Estimation from spectrography is one of the oldest methods of formant frequency measurement. A spectrogram is a three-dimensional display of time, frequency, and amplitude, where frequency is displayed as a function of time, and amplitude is represented by relative darkness (Borden , Harris, and Raphael, 1994). Spectrograms provide information concerning the vibratory characteristics of the vocal folds as well as the properties of the resonator or vocal tract.

Using wideband spectrography, formant frequencies can be estimated. This is accomplished by using a bandwidth that is sufficiently wide as to include multiple harmonics but sufficiently narrow as to include only one formant. Bandwidths of high relative darkness indicate a resonance peak within that range of frequencies. Formant frequencies are typically measured as the center frequency of the band Thus, errors in measurement of formant frequency can be as high as ± one-half the bandwidth

Spectral Analysis

An amplitude spectrum is a two-dimensional representation of the component frequencies of a signal where amplitude is displayed as a function of frequency An amplitude spectrum of a complex periodic waveform can be calculated through use of a Fourier transform.

Using spectral analysis, formants can be estimated by determining which harmonic corresponds to a peak in the spectral envelope. When a signal is comprised of narrowly spaced harmonics, spectral peaks are likely to coincide with the actual formant frequency. However, when a signal is comprised of widely spaced harmonics, spectral peaks are less likely to coincide with the actual formant frequency resulting in erroneous estimation.

Linear Predictive Coding

Linear predictive coding (LPC) is a time domain approach based on time-series analysis where at any point in time, the amplitude of the time domain waveform can be predicted by a linear combination of previous amplitudes In LPC, each previous amplitude value is multiplied by a predictor coefficient. Estimated amplitudes are compared to actual amplitudes using least squares methodology. Predictor coefficients are modified until the error is reduced to a minimum (Kent & Read, 1992)

The predictor coefficients generated by LPC can be used to calculate formant frequencies (Wakita, 1996). Because this calculation does not depend on the location of harmonics, LPC formant frequency estimation is more accurate than other methods when fundamental frequency is below 350 Hz (Monsen & Engebretson, 1983). However, LPC analysis suffers the same limitations as other methods when fundamental frequency rises above 350 Hz

Problems With Formant Estimation at High Fundamental Frequency

Researchers have long reported formant frequency values for high-pitched speakers such as women and children (Peterson & Barney, 1952, Hillenbrand et al, 1995). However, as White (1998) and Hertegard and Guaffin (1994) point out, formant frequencies become increasingly difficult to estimate as F_0 increases due to the corresponding increase in distance between the harmonics.

Spectrography

At high pitches, spectrography is the least accurate of the three methods of formant frequency estimation. Even when using wideband spectrography, there is usually only one harmonic per band. Each harmonic appears as a wide, dark band, and therefore, the exact frequency of the harmonics cannot be obtained. The possibility of error will be $\pm$ ½ the bandwidth. Amplitude of the harmonic typically cannot be estimated, because the subtle changes in darkness from one band to another are not easily perceived by the naked eye. Narrow bandwidth spectrograms are somewhat better than broadband in these situations but are still a very poor method of formant frequency estimation at high pitches. Narrowband spectrograms provide a more accurate estimate of harmonic frequency, but still suffer from poor amplitude resolution. Thus, at best, a spectrographic analysis at high pitches provides essentially a crude spectral analysis with poorly resolved amplitudes

Spectral Analysis

Higher fundamental frequencies can be a source of error for spectral analysis This is because the wider harmonic spacing offers less information concerning the exact location of formant frequencies. Correspondingly, two voice sounds may be produced with nearly identical vocal tract configurations, yet may be perceived very differently by the ear. This happens because the harmonics are spaced differently and may line up with the formant frequencies of one spectrum and not with the other Investigators must take great care not to assume that the formant frequency corresponds to the frequency of the strongest component in the spectrum (Lindblom, 1962). Lindblom and Sundberg (1971) suggest that the typical formant frequency measurement error using spectral analysis may be as high as $F_o/4$.

Linear Predictive Coding

Because LPC uses time-domain generated predictor coefficients, its accuracy depends on how much information is contained in the time-domain waveform. While low-pitched time-domain waveforms exhibit distinct shapes for specific vowels, these shapes tend to converge towards a simple sinusoidal shape as F_o increases This reduced information results in inaccurate formant frequency estimations above around 350 Hz (Monsen & Engebretson, 1983).

Typical Solutions To The Problem

Artificial Voice Source

Substitution of a low frequency artificial sound for vocal fold vibration is one approach to solving the problem of estimating formant frequencies at high pitches. There are several methods of source substitution. One method is the use of an artificial larynx (Coleman, 1976) In this method, an artificial larynx is held to a person's neck while they shape their oral cavity so that it is ready to resonate for particular vowels. Another method of source substitution is using computer-generated noise to stimulate a transducer placed on the neck (Hertegard & Gauffin, 1994)

There are problems associated with using a vibrator-produced tone as a substitution for the normal laryngeal tones. When using an artificial voice source, if the glottis is open, the trachea will be coupled acoustically to the rest of the vocal tract, thereby altering its acoustic characteristics (Coleman, 1976). Also, when using an artificial sound source, the speaker may not employ the same jaw opening or laryngeal height that they would during phonation. Hertegard and Gauffin (1994), tried to overcome these problems by encouraging subjects to maintain the articulation position during silent periods. In spite of these measures, they obtained lower than expected formant frequency values, suggesting that the procedure was not entirely successful.

Miller et. al (1997) tried to determine the degree of similarity and/or difference in acoustic and spatial dimensions of the vocal tract during normal phonation to the same measures during the production of two types of aperiodic phonation (ingressive and vocal fry). Formant frequencies were measured using linear predictive coding (LPC) and spectral analysis. Spatial dimensions of the vocal tract were obtained using magnetic resonance imaging (MRI) Miller and colleagues found that formant frequencies obtained from aperiodic phonation differed from those obtained from normal phonation by 30-60 Hz. They concluded that such variation is within the limits of measurement error. However, when they compared the spatial dimensions of the vocal tract obtained from normal phonation and aperiodic phonation, obvious differences were observed Thus, they concluded that in spite of similar formant frequencies, vocal tract shape and size does not remain constant across all three tasks.

Sliding Pitch

White (1998) attempted to solve the problem of formant estimation in high-pitched children's voices by using a sliding pitch paradigm. Twenty-nine 11-year-old Swedish children produced four spoken or sung vowels with a fundamental frequency that slowly varied over a range of at least one fifth. Through examination of peak harmonic amplitude, formant frequencies can be estimated. While this method eliminates the possibility of an erroneous coupling to the trachea, the sweeping pitch changes increase the likelihood of laryngeal and articulatory movement. Experienced choral members were used to avoid laryngeal movement often associated with inexperienced singers However, White makes no mention of laryngeal monitoring nor does she report actual measurements of laryngeal movement.

Inverse Filtering

Because inverse filtering requires accurate estimation of formant frequencies and bandwidths, researchers interested in glottal airflow characteristics have developed methods of formant frequency estimation based on the concept of inverse filter tuning. Typically, the frequencies and bandwidths of the inverse filter are altered until the resulting glottal volume velocity waveform has a flat closed phase with no formant ripple (Gauffin-Lindquist, 1964). However, as Fant (1970) and Rothenberg (1987) have shown, the closed phase observed in high-pitched phonation is very short and, due to source-filter interaction, there is a significant amount of ripple that remains even after successful filtering of formant frequencies. Such source-filter interaction is particularly prominent when the first formant frequency is close to the fundamental frequency.

Rothenberg (1981, 1987) and Hertegard and Gauffin (1994) have attempted to solve the problem of formant frequency estimation in high-pitched voices using simultaneous airflow and electroglottogram (EGG) measures. The moment and duration of closure observed in the EGG waveform were used as criteria for inverse filtering of the airflow waveform That is, formant frequencies and bandwidths of the inverse filter were altered until the moment of closure and the duration of the closed phase of the glottal volume velocity waveform most closely approximated that of the EGG waveform. Using such a technique, it is possible to obtain improved estimates of first formant frequency

Radiographic Assessment of Vocal Tract Shape

Three dimensional information about the vocal tract shape and size can be obtained by acquiring a series of image slices in one or more anatomical planes through modern imagine techniques, such as Magnetic Resonance Imaging (MRI) or Electronic Beam Computed Tomography (EBCT). These techniques are discussed in detail in a series of articles by Brad Story and colleagues (e.g., Story, Titze, & Hoffman, 1996; Story, Hoffman, & Titze, 1996).

MRI places no known danger on human subjects, which makes it a desirable imaging technique. However, it also has several disadvantages For example, it may take as long as 10 to 15 minutes to complete. Furthermore, due to the low hydrogen concentration, teeth and bone structures appear to be the same gray scale value as air, making them poorly imaged.

In contrast with the MRI, the EBCT has the following advantages: at the walls of the vocal tract, clear definition of the air-tissue interface is apparent, it images teeth, and a volumetric scan with a clear resolution can be obtained within tens of seconds. While these characteristics appear to encourage the use of EBCT, it has actually been used sparingly due to the fact that it uses ionizing radiation, which may make the technique unsafe.

Both imaging methods provide three-dimensional representations of the vocal tract. Using cross-sectional areas, formant frequencies can be calculated (Wakita, 1979). While MRI presents reduced risk to subjects, it is impractical because of the length of time required to obtain an image. On the other hand, while EBCT provides a much sharper picture and can be administered in a shorter time period, it presents increased health risks to subjects. Both techniques are difficult for the average researcher to use because they require access to expensive medical equipment and coordination with medical professionals Additionally, computing cross-sectional areas from the three-dimensional displays is extremely time-consuming.

Summary of the Literature Review

Numerous methods of formant frequency estimation are described in the literature, including: spectrography, spectral analysis, and LPC. Each of these methods are highly inaccurate estimations of formant frequency where F_0 is high due to the wide spacing of harmonics. Some typical solutions to the problem are the use of one or more of the following: an artificial voice source, sliding pitch, inverse filtering, and/or radiographic assessment of vocal tract shape. As yet, the accuracy of formant frequency estimation using any of these techniques is unknown.

PURPOSE

The purpose of this study was to investigate the effectiveness of using an artificial larynx as a replacement sound source for measurement of formant frequencies. Specifically, this study compared formant frequencies 1-4 obtained from voiced productions of the vowels /ɑ/ and /ɪ/ at a comfortable pitch and loudness to the same measures obtained using artificial laryngeal stimulation. Data were obtained from normally speaking males. The following questions were asked:

1. Do formant frequencies obtained from artificial laryngeal stimulation differ from those obtained from natural phonation?

The hypothesis is that overall, differences will be observed between formant frequencies obtained from artificial laryngeal stimulation and those obtained from natural phonation. This is based on the fact that accurate estimation requires identical structural positions to those used in natural speech.

2. Which method of artificial laryngeal stimulation, neck placement or oral insertion, most accurately measures formant frequency as compared to natural phonation?

It is hypothesized that an oral stimulation wherein the vocal folds continue to vibrate will provide a more accurate estimate of formant frequencies than does a neck stimulation that requires a cessation of vocal fold vibration. This is based on the fact that a lack of vocal fold closure results in a coupling to the trachea, causing inappropriate resonances and anti-resonances to be added to the signal (Coleman, 1976)

CHAPTER TWO

METHODS

SUBJECTS

Description of Subjects

Because accurate formant frequency measurements can only be made from low-pitched voices, the 20 subjects were male only. Nineteen of the subjects met the following criteria

1. chronological age between 18·00 and 45:00 years;
2. bilateral hearing within normal limits as determined by a 20 dB HL hearing screening at 500 Hz, 1000 Hz, and 4000 Hz (ASHA, 1990) administered by the principal investigator;
3. no voice disorder at the time of the experiment as judged perceptually by a certified speech-language pathologist;

One of the subjects met criteria 2 and 3, but had a mild bilateral high frequency hearing loss

Subject Recruitment

Subjects recruited were students enrolled in Psychology 110 at the University of Tennessee or were graduate students in the Department of Audiology and Speech Pathology at the University of Tennessee. Psychology 110 students received extra credit for their participation.

PROCEDURES

Tasks

Each subject was audio recorded while completing three tasks. Each task was performed on the vowels /ɑ/ and /ɪ/. Subjects performed each task at a comfortable pitch and loudness.

Task 1

Task 1 functioned as a control task. During task 1, each subject produced the sustained vowels /ɑ/ and /ɪ/ for 4 seconds.

Task 2

In task 2, a neck placement of the artificial larynx was used. In such a task, the subject cannot vocalize during artificial stimulation due to damping as the sound passes through the neck. While holding an artificial larynx to the neck, each subject produced a sustained vocalization for 2 seconds and then, while continuing to hold all structures in place, ceased vocal fold vibration, held their breath, and stimulated the vocal tract by engaging the artificial larynx for 2 seconds.

Task 3

In task 3, an oral placement of the artificial larynx was used. Such a configuration allowed the subject to phonate during artificial laryngeal stimulation. While placing the oral tube of an artificial larynx in the oral cavity, each subject produced a sustained vocalization for 4 seconds. The artificial larynx was activated for the last 2 seconds of phonation.

Equipment

Each subject was recorded while standing in a Suttle double-walled sound-treated booth with a mounted Sony condenser microphone positioned 12 inches from the lips at a ninety-degree angle Acoustic data were recorded on digital audio tapes (DAT) using a Sony 60ES DAT recorder. Artificial laryngeal vibration was provided using a Servox Inton Electronic Speech Device. Acoustic data was analyzed using the Computerized Speech Lab (CSL) (Kay Elemetrics, Pine Brook, NJ).

Data Measurements

Formant Frequencies

The purpose of this study was to compare the formant frequencies obtained using an artificial sound source to those actually produced during phonation. Consequently, frequencies of formants 1-4 were measured from voiced segments and from artificially stimulated segments for all three tasks and on two vowels.

For each task, two measurements of formant frequencies 1-4 were performed. The first measurement was complete at second 1 of the task. The second measurement was completed at second 3 of the task. For task 1, this resulted in two sets of formant frequencies, each obtained from voiced segments. For task 2, formant frequencies 1-4 were obtained from the midpoint of vocal fold vibration and from the midpoint of artificial laryngeal stimulation. For task 3, formant frequencies 1-4 were obtained midway between onset of vocal fold vibration and initiation of artificial laryngeal stimulation and at the midpoint of artificial laryngeal stimulation. Order of task presentation was counter-balanced.

Sampling rates for all acoustic analyses were 10,000 Hz. Formant frequencies were estimated using Linear Predictive Coding (LPC) in combination with a Fast Fourier Transform (FFT). LPC parameters used were as follows: filter order = 10, pre-emphasis = .09, and framelength = 30 ms. FFT analyses was performed using a pre-emphasis of 0.9 and a frame length of 1024 ms

Reliability

To obtain intrajudge reliability measures, all formant frequencies were re-measured, 6 weeks later, by the investigator for 4 randomly selected subjects The Pearson product moment correlation for intrajudge measures was .99. To obtain interjudge reliability, a graduate student familiar with formant frequency estimation measured all formant frequencies for 4 randomly selected subjects The Pearson product moment correlation for interjudge measures was .98.

Analyses

Group and individual analyses were performed. Group analyses consisted of a 3-way repeated measures analysis of variance (ANOVA) and multiple post hoc paired t-tests. Individual analyses consisted of comparison of subject data for tasks 2 and 3, both of which use artificial laryngeal stimulation, to group data for task 1, the control task

A logarithmic (base 10) transformation was applied to all formant frequency data prior to statistical analysis. This transformation was necessary due to large differences in variance observed between lower frequency and higher frequency formants

CHAPTER THREE

RESULTS

DESCRIPTIVE STATISTICS

Raw data are presented in Appendix A. The mean (M), standard deviation (SD), range, skewness, and kurtosis for formants one through four, for the vowels /ɑ/ and /ɪ/, are reported in Tables 1 and 2 respectively. Kurtosis and skewness are considered normal at 0.0. A high negative kurtosis value yields a peaked, or leptokurtic distribution. A high positive kurtosis value yields a flattened, or platykurtic distribution. A large negative skewness value represents a negatively skewed distribution. A large positive skewness value represents a positively skewed distribution (Bentler, 1995)

GROUP ANALYSES

Repeated Measures Analysis of Variance

The first research question sought to determine whether formant frequency measurements obtained from natural phonation differ from those obtained from artificial laryngeal stimulation. To partially answer this question, a repeated measures analysis of variance (ANOVA) was performed to determine the effects of task, formant, and time on formant frequency for each of the vowels /ɑ/ and /ɪ/.

Recall that all three tasks measured formant frequencies from natural phonation at second one. At second 3, task 1 measured formant frequencies from natural phonation, while tasks 2 and 3 measured formant frequencies from artificial laryngeal stimulation.

Table 1

Descriptive Statistics for Formant Frequencies 1-4 for the Vowel /ɑ/ (N = 20)

Task	Second 1 F1	Second 1 F2	Second 1 F3	Second 1 F4	Second 3 F1	Second 3 F2	Second 3 F3	Second 3 F4
Task 1								
Mean	681.44	1184.3	2535.2	3505.8	679.00	1174 8	2519.4	3509 5
SD	86.57	107.29	138.33	194.89	82.31	100.10	170.58	211.84
Range	337	382	480	836	.21	334	602	982
Skewness	-.482	.030	-.466	.475	.046	-.005	-.416	-.380
Kurtosis	.326	-.835	-.540	.755	-.320	-1.090	-.363	1.373
Task 2								
Mean	694.91	1144.7	2559.8	3468.5	691.94	1098.2	2391.8	3364.6
SD	66.76	100.52	132.35	213.45	92.56	94.59	183.79	325 47
Range	271	359	509	849	352	307	685	1133
Skewness	-.988	-.137	-.019	.397	-.988	-.137	.354	-.342
Kurtosis	1.676	-.660	-.140	.028	1.676	-.660	-.392	-.922
Task 3								
Mean	687.86	1131.9	2523.4	3454.8	796.53	1195.1	2327 6	3331.5
SD	97.40	88.30	182.45	218.92	115.66	45.62	501.30	265.73
Range	422	279	708	753	507	198	2483	844
Skewness	-1.037	.005	.523	.396	.541	-.150	-4.063	-1.233
Kurtosis	2.393	-1.298	-.216	-.770	.979	.743	17.549	.593

Formant Frequency in Hz

Table 2

Descriptive Statistics for Formant Frequencies 1-4 for the Vowel /i/ (N = 20)

	Formant Frequency in Hz							
Task	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
Task 1								
Mean	284.96	2212.4	2793.6	3449.9	288.55	2194.9	2745.1	3397.02
SD	34.76	132.41	186 51	138.85	32.82	135.77	199.02	164.84
Range	138	506	571	567	126	470	639	555
Skewness	.429	.159	.207	-1.009	.436	.363	.310	-.526
Kurtosis	-.188	-.373	-1.403	1.171	-.308	-.715	-1.132	-.624
Task 2								
Mean	285.64	2230.3	2754.6	3450.1	531.56	2041.1	2747.5	3463.27
SD	38.40	120.21	179.52	237.58	214.74	312.88	337.81	306.15
Range	130	388	663	1154	629	1062	1241	1011
Skewness	.720	-.344	-.313	.050	.661	-1.417	.387	-1.385
Kurtosis	-.666	-1.133	-.539	1.870	-.423	1.225	.033	1 057
Task 3								
Mean	303.55	2162.7	2583.0	3412.6	397.35	2107.9	2528.3	3520 8
SD	36.74	129.02	206.61	177.77	338 45	223.87	144 39	438.99
Range	136	563	772	705	1148	808	519	2114
Skewness	-.302	.874	-.066	-.388	2 079	-1.328	437	913
Kurtosis	-.394	1.804	- 439	-.058	3.200	1.247	- 463	3 663

Thus, examination of the one-way effects of task, format, or time will not provide useful information. For this reason, only two interactions will be discussed below: (1) task x time and (2) task x formant x time All ANOVA results for the vowels /ɑ/ and /ɪ/ are summarized in Tables 3 and 4, respectively.

When the two-way interaction of task and time is considered, formant frequencies of the vowel /ɑ/ were found to differ significantly ($F = 6.86$, $df = 2$, $p = .003$). Likewise, formant frequencies for /ɑ/ were found to be significantly different when the three way interaction between task, formant, and time is considered ($F = 5\ 05$, $df = 6$, $p = <.001$). Similar results were obtained for the vowel /ɪ/. Formant frequencies for the vowel /ɪ/ were significantly different across task and time ($F = 6.04$, $df = 2$, $p = .005$) and across task, formant, and time, ($F = 8.83$, $df = 6$, $p = <\ 001$).

While not conclusive, these results suggest that differences were observed between formant frequencies measured from natural phonation and those measured from artificial laryngeal stimulation for both vowels. Additionally, the significant interaction of task, formant, and time for both vowels suggests that differences in formant measurement between those obtained from natural phonation and those obtained from artificial laryngeal stimulation are not the same for each formant. In order to answer the research questions posed in the study, these interaction effects must be examined in greater detail.

Table 3

Analysis of Variance Computed for the Repeated Measures of Task, Formant, and Time on the Dependent Variable, Formant Frequency, for the vowel /ɑ/ (N = 20)

Repeated Measures	Sum of Squares	*df*	*F* Ratio	Significance Level
Task	.01	2	2.64	084
Formant	35.59	3	3892.81	<.001
Time	.0001	1	.11	.745
Task x Formant	.05	6	7.03	<.001
Task x Time	.02	2	6.86	.003
Formant x Time	5.5	3	5.54	.002
Task x Formant x Time	5.1	6	5.05	<.001

Table 4

Analysis of Variance Computed for the Repeated Measures of Task, Formant, and Time, on the Dependent Variable, Formant Frequency for the vowel /i/ (N = 20)

Repeated Measures	Sum of Squares	*df*	*F* Ratio	Significance Level
Task	.07	2	7.50	.002
Formant	79.78	3	3407.75	< 001
Time	.03	1	7.89	.011
Task x Formant	.25	6	7.94	< 001
Task x Time	.06	2	6.04	.005
Formant x Time	.22	3	11.92	<.001
Task x Formant x Time	.29	6	8.83	<.001

Post Hoc Analyses

One possible way to assess whether or not formant frequency measurements obtained from natural phonation differ from those obtained from artificial laryngeal stimulation would be to compare measurements obtained at second 1 (natural phonation on all tasks) to those obtained at second 3 (artificial laryngeal stimulation on tasks 2 and 3) for each vowel and formant. A second way to assess this question would be to compare measurements taken at second 3 of task 1 (natural phonation) to those taken from second 3 for tasks 2 and 3 (artificial laryngeal stimulation). Both approaches are taken below.

Differences Across Time

Post hoc t-tests were performed comparing measurements from second 1 to those from second 3 for each formant for the vowels /ɑ/ and /i/. Results are presented in Table 5 and Table 6, respectively.

The vowel /ɑ/. For task 1, no significant differences in formant frequency were found across time for any formant. This would be expected since task 1 used natural phonation on seconds 1 and 3. For task 2, there was a significant decrease in frequency between second 1 and second 3 for F2 ($df = 19$ and $p = .002$) and for F3 ($df = 19$ and $p = .007$). For task 3, there was a significant increase in frequency between second 1 and second 3 for F1 ($df = 19$ and $p = .023$) and for F2 ($df = 19$ and $p = .007$), while there

Table 5

Post Hoc t-tests Comparing Formant Frequency across Time for each Task and Formant for the Vowel /ɑ/.

	Mean Log_{10} of Frequency			
	Second 1	Second 3	*df*	Significance Level
Task 1				
F1	2.8299	2.8288	19	.819
F2	3.0718	3.0685	19	.355
F3	3.4034	3.4003	19	.342
F4	3.5442	3.5445	19	.936
Task 2				
F1	2.8399	2 8364	19	.801
F2	3.0571	3 0391	19	.002
F3	3 4076	3.3775	19	.007
F4	3 5394	3.5249	19	.131
Task 3				.
F1	2.8327	2 8969	19	.023
F2	3.0526	3.0771	19	.007
F3	3.4009	3.3875	19	.047
F4	3.5376	3.5212	19	098

Table 6

Post Hoc t-tests Comparing Formant Frequency across Time for each Task and Formant for the Vowel /i/.

	Mean Log_{10} of Frequency			
	Second 1	Second 3	*df*	Significance Level
Task 1				
F1	2.4518	2.4576	19	.283
F2	3.3441	3.3406	19	.188
F3	3.4452	3.4375	19	001
F4	3.5375	3.5306	19	.083
Task 2				
F1	2.4522	2.6923	19	<.001
F2	3.3477	3.3041	19	.027
F3	3.4392	3.4359	19	.773
F4	3.5368	3.5377	19	.919
Task 3				
F1	2.4791	2.5014	19	.725
F2	3.3343	3.3213	19	197
F3	3.4108	3.4022	19	.253
F4	3.5325	3 5435	19	.343

was a significant decrease in frequency for F3 (*df* = 19 and *p* = .047). These differences suggest that, for the vowel /ɑ/, formant frequencies obtained from natural phonation differ from those obtained from artificial laryngeal stimulation.

The vowel /i/. For task 1, no significant differences in formant frequency were found between second 1 and second 3 for F1, F2, and F4. Surprisingly, a significant decrease in formant frequency from second 1 to second 3 was observed for F3 (*df* = 19 and *p* = .001) on this control task. For task 2, there was a significant increase in frequency between second 1 and second 3 for F1 (*df* = 19 and *p* = <.001) and a significant decrease in frequency between second 1 and second 3 for F2 (*df* = 19 and *p* = .027). For task 3, no significant differences across time were observed. These results suggest that, for the vowel /i/, formant frequencies obtained from natural phonation differ from those obtained from artificial laryngeal stimulation using a neck placement (task 2) but not from those obtain from artificial laryngeal stimulation using an oral placement (task 3).

Differences Across Tasks

Post hoc t-tests were performed comparing measurements from second 3 across tasks for each formant for the vowels/ɑ/ and /i/. The following comparisons were made: (1) natural phonation (task 1) compared to artificial laryngeal stimulation with a neck placement (task 2) and (2) natural phonation (task 1) compared to artificial laryngeal stimulation with an oral insertion (task 3). Results of these analyses for the vowel /ɑ/ are presented in Table 7 while those for the vowel /i/ are presented in Table 8.

Table 7

Post Hoc t-tests Comparing Formant Frequency at Second 3 across Tasks for each Formant for the Vowel /ɑ/.

Formant	Mean Log_{10} of Frequency at Second 3			Comparisons			
	Task 1	Task 2	Task 3	Task 1 - Task 2		Task 1 - Task 3	
				df	α	df	α
1	2.8288	2 8364	2.8969	19	.602	19	.001
2	3.0685	3.0391	3.0771	19	<.001	19	.347
3	3.4003	3.3775	3.3375	19	.045	19	.237
4	3.5445	3.5249	3.5212	19	.076	19	.054

Table 8

Post Hoc t-tests Comparing Formant Frequency at Second 3 across Tasks for each Formant for the Vowel /i/.

Formant	Mean Log_{10} of Frequency at Second 3			Comparisons			
	Task 1	Task 2	Task 3	Task 1 - Task 2		Task 1 - Task 3	
				df	α	df	α
1	2.4576	2.6923	2 5014	19	<.001	19	475
2	3.3406	3.3041	3.3213	19	.076	19	.085
3	3.4375	3.4359	3.4022	19	.903	19	<.001
4	3.5306	3.5377	3.5435	19	.432	19	.302

The vowel /ɑ/. Formant frequencies at second 3 were significantly lower for task 2 as compared to task 1 for F2 (*df* = 19 and p = 001) and F3 (*df* = 19 and p = .045), and were nearly significantly lower for F4 (*df* = 19 and p = 076). These results are consistent with those obtained in the previous comparison across time for task 2. Formant frequencies at second 3 were significantly higher for task 3 as compared to task 1 for F1 (*df* = 19 and p = .001), while formant frequencies at second 3 were nearly significantly lower as compared to task 1 for F4 (*df* = 19 and p =.054). These results suggest that, for the vowel /ɑ/, formant frequencies obtained from natural phonation differ from those obtained from artificial laryngeal stimulation.

The vowel /i/ Formant frequencies at second 3 were significantly higher for task 2 as compared to task 1 for F1 (*df* = 19 and p < 001) and were nearly significantly lower as compared to task 1 for F2 (*df* = 19 and p = .076). These results are consistent with those obtained in the previous comparison across time for task 2 Formant frequencies at second 3 were significantly lower for task 3 as compared to task 1 for F3 (*df* = 19 and p < .001. As in the previous analysis comparing differences across time, these results suggest that, for the vowel /i/, formant frequencies obtained from natural phonation differ from those obtained from artificial laryngeal stimulation using a neck placement (task 2). Contrary to the previous analysis, however, this analysis also suggests that formant frequencies obtain from natural phonation differ somewhat from those obtain from artificial laryngeal stimulation using oral insertion.

Group Plots

Differences in formant frequency across time and task are presented in Figures 1 - 8. These differences can be understood through consideration of Equation 1:

$$|D_o| = |\log_{10}(F_a/F_n)| \qquad \textbf{Equation 1}$$

where D_o equals differences in Log10 of formant frequency, F_a equals formant frequency measured through artificial laryngeal stimulation and F_n equals the formant frequency measured through natural phonation. For both /ɑ/ and /i/, $|D_o|$ is less than .05 for all comparisons across task and time, with one exception. This means that F_a differs less than 12% from F_n in all but one comparison. For the vowel /i/, F1, task 2 at second 3, $D_o > .3$. This means that F1 of /i/ increased by over 100% when using artificial laryngeal stimulation with a neck placement as compared to natural phonation.

Summary of Group Analyses

In general, the group analyses demonstrate that artificial laryngeal stimulation elicits formant frequency measurements that differ significantly from those obtained from natural phonation. Close inspection of the results suggests that patterns of differences exist depending on vowel, task, and formant.

Vowel /ɑ/

For the vowel /ɑ/, all post hoc analyses revealed significantly lower formant frequencies for F2 and F3 when estimation was performed using artificial laryngeal stimulation with a neck placement as compared to natural phonation. Consistently higher frequencies for F1 were obtained using artificial laryngeal placement with an oral insertion as compared to natural phonation for F1 on this same vowel.

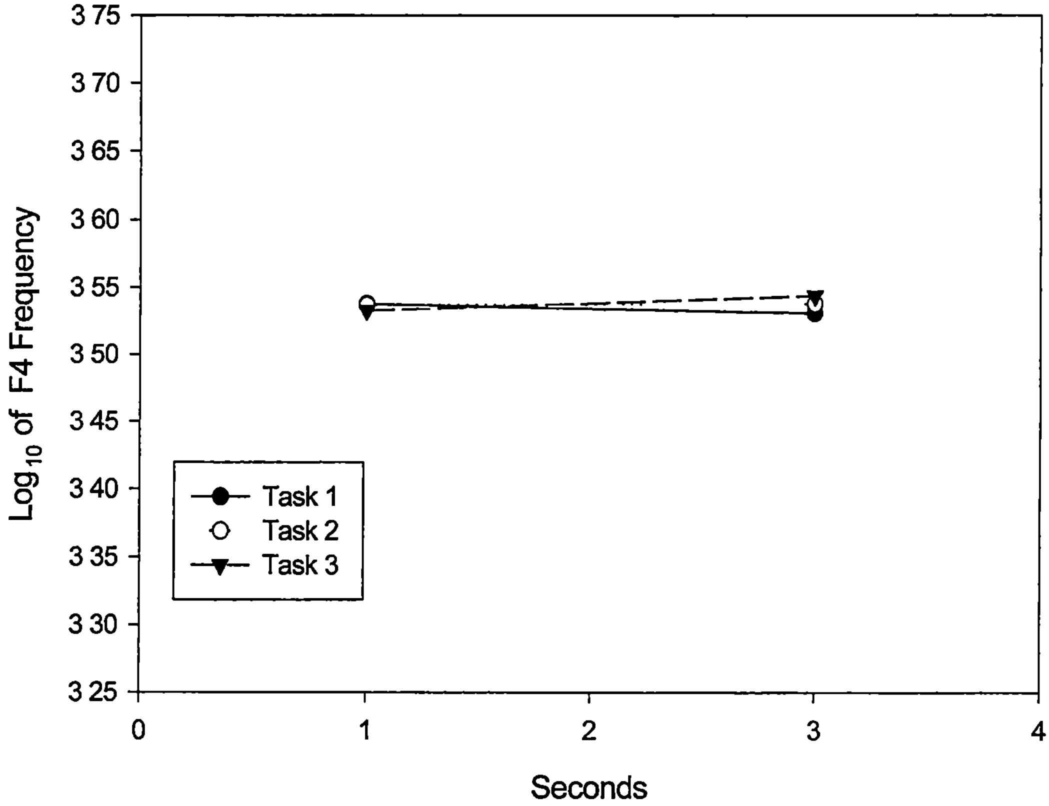

Figure 1: Mean Log10 of F1 formant frequency for the vowel /ɑ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20)

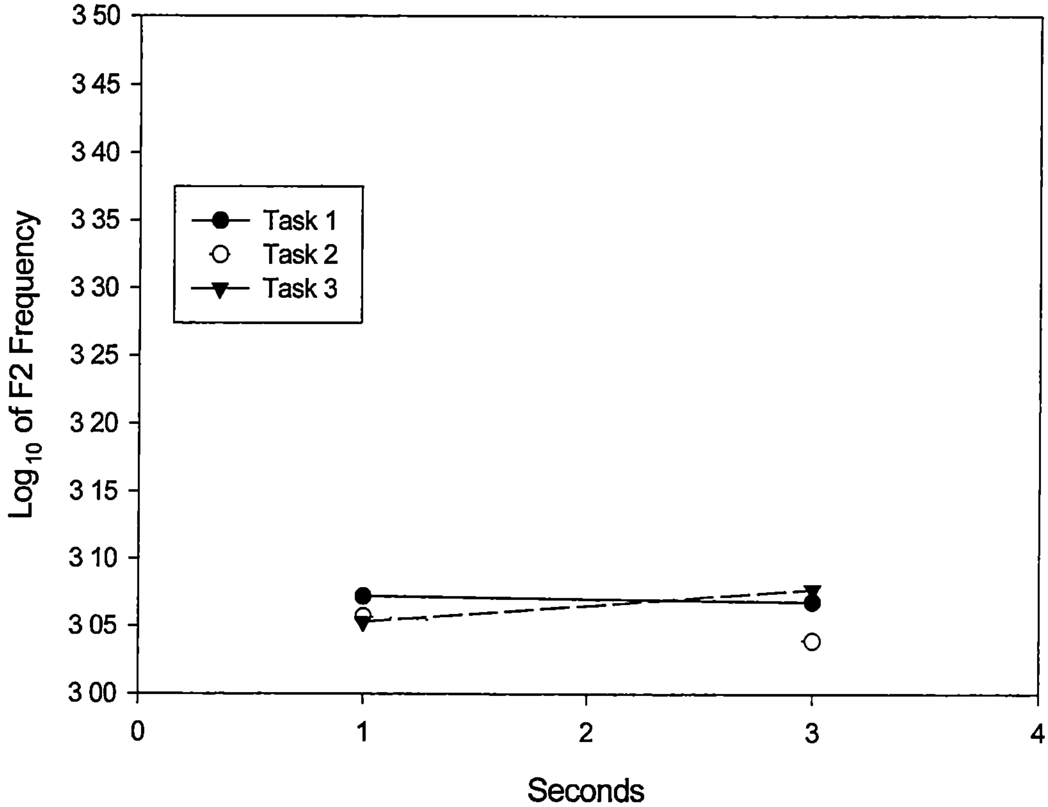

Figure 2: Mean Log10 of F2 formant frequency for the vowel /ɑ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20).

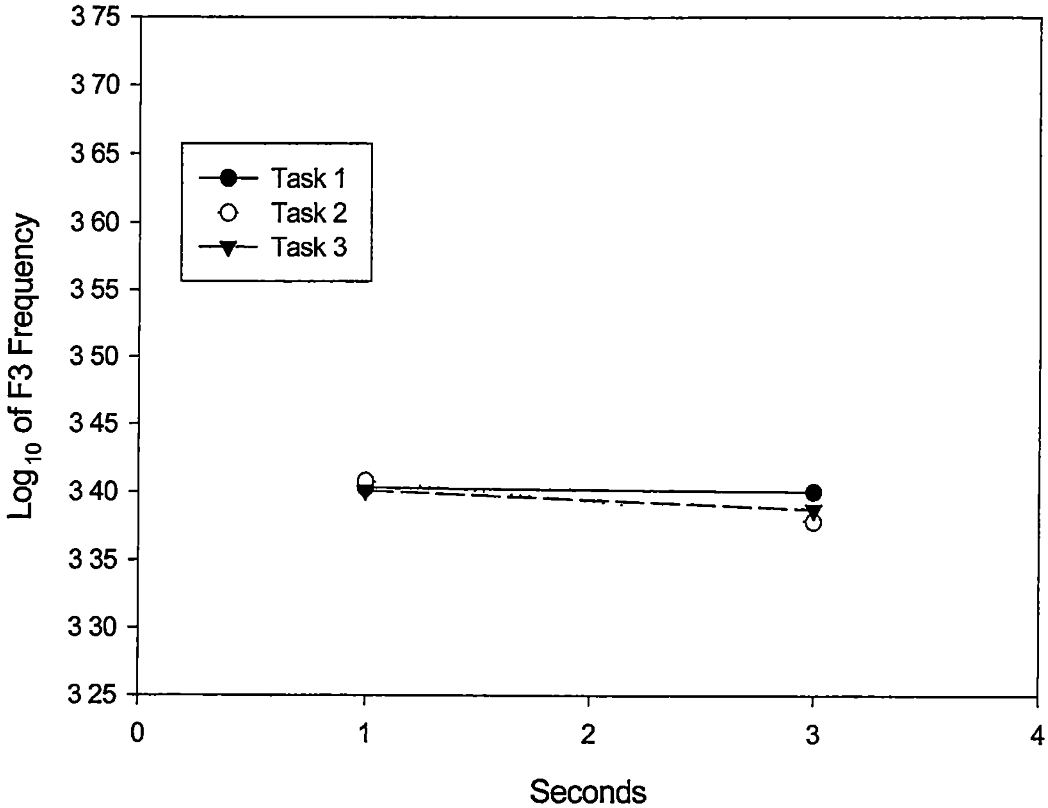

Figure 3: Mean Log10 of F3 formant frequency for the vowel /ɑ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20).

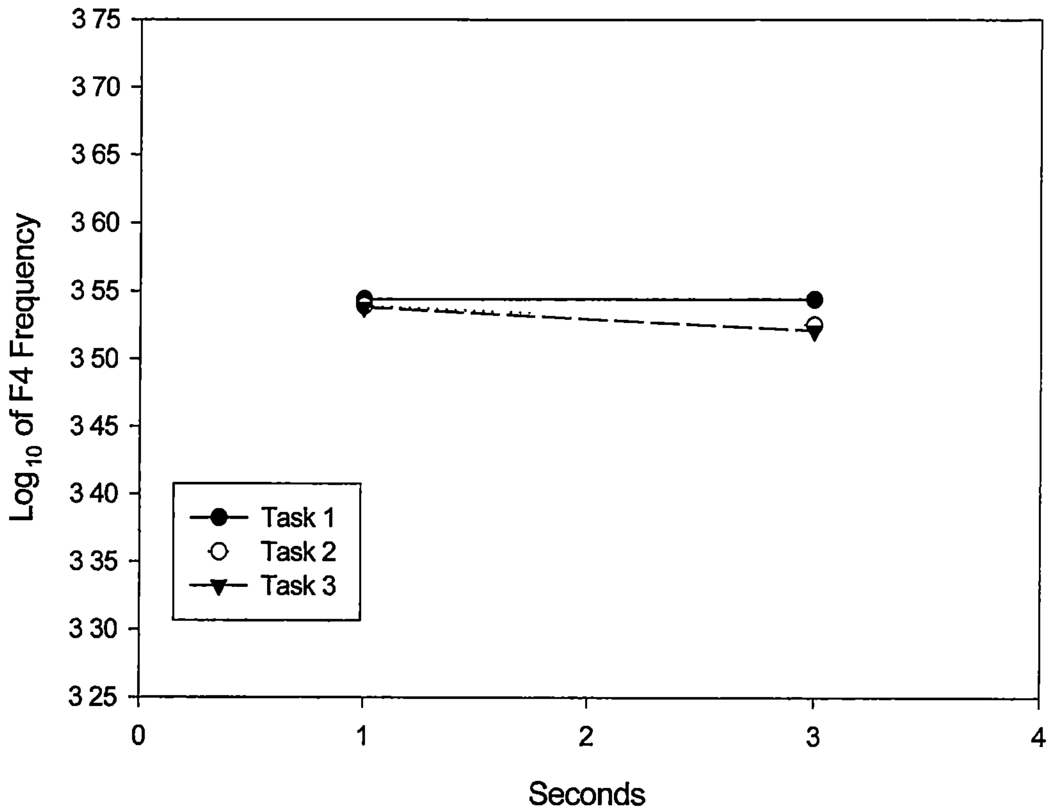

Figure 4: Mean Log10 of F4 formant frequency for the vowel /ɑ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20).

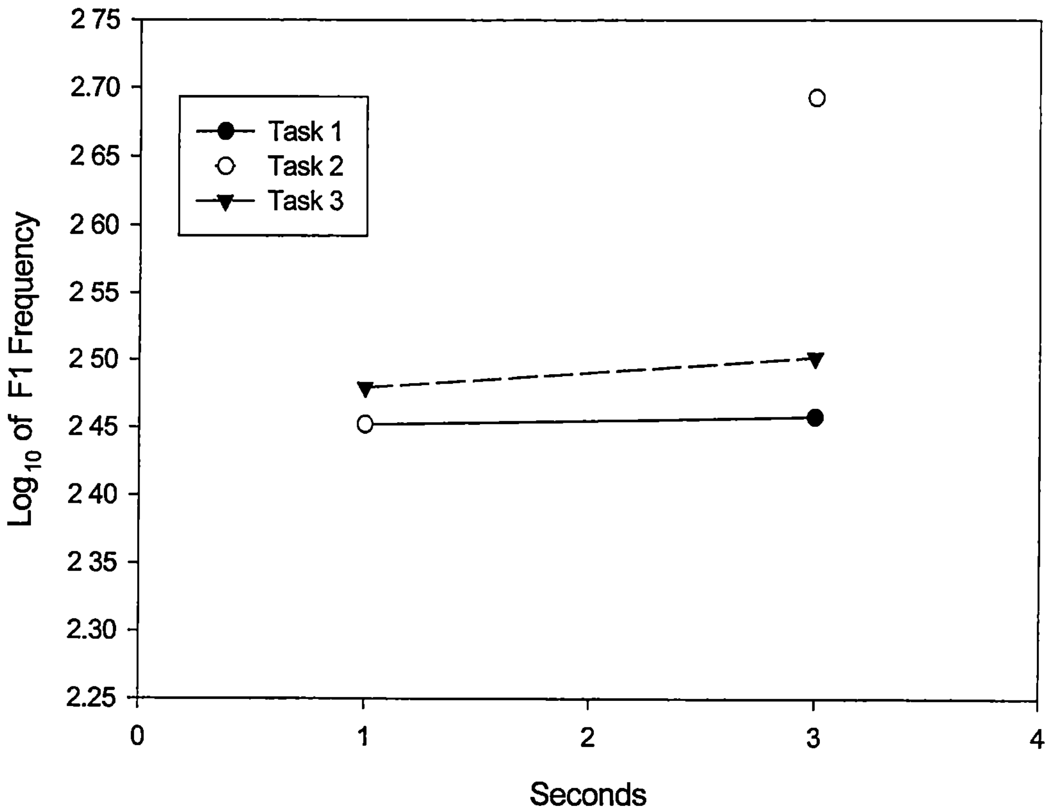

Figure 5: Mean Log10 of F1 formant frequency for the vowel /ɪ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20).

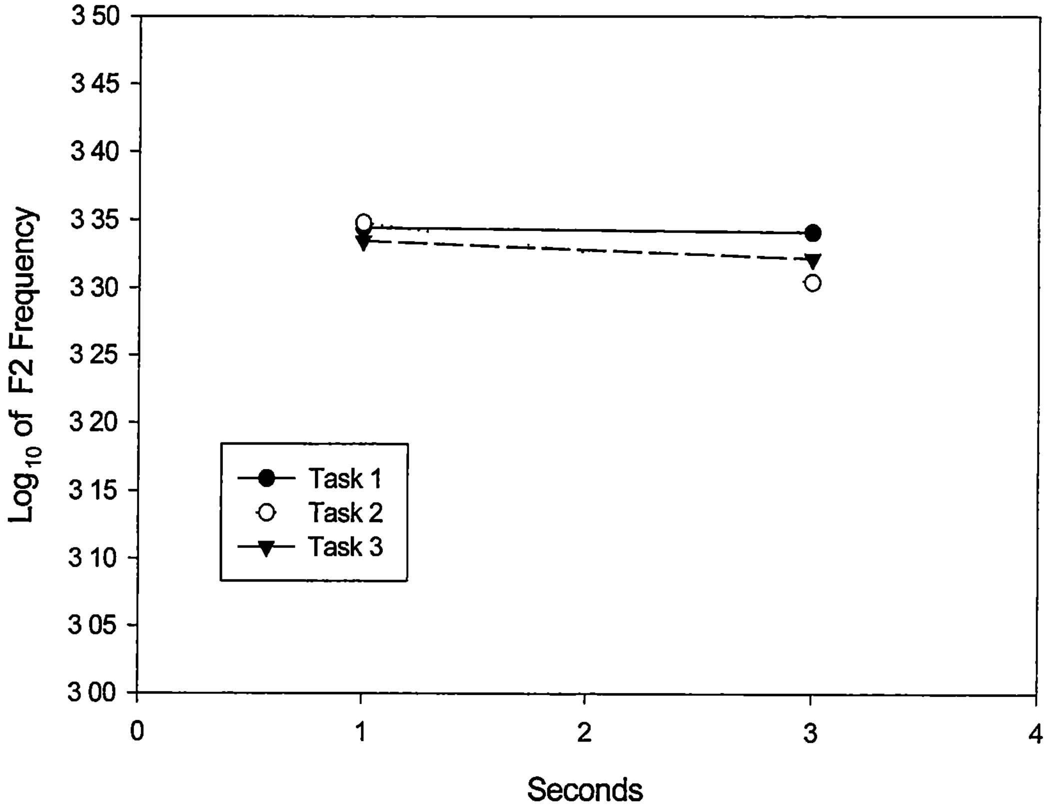

Figure 6: Mean Log10 of F2 formant frequency for the vowel /i/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20).

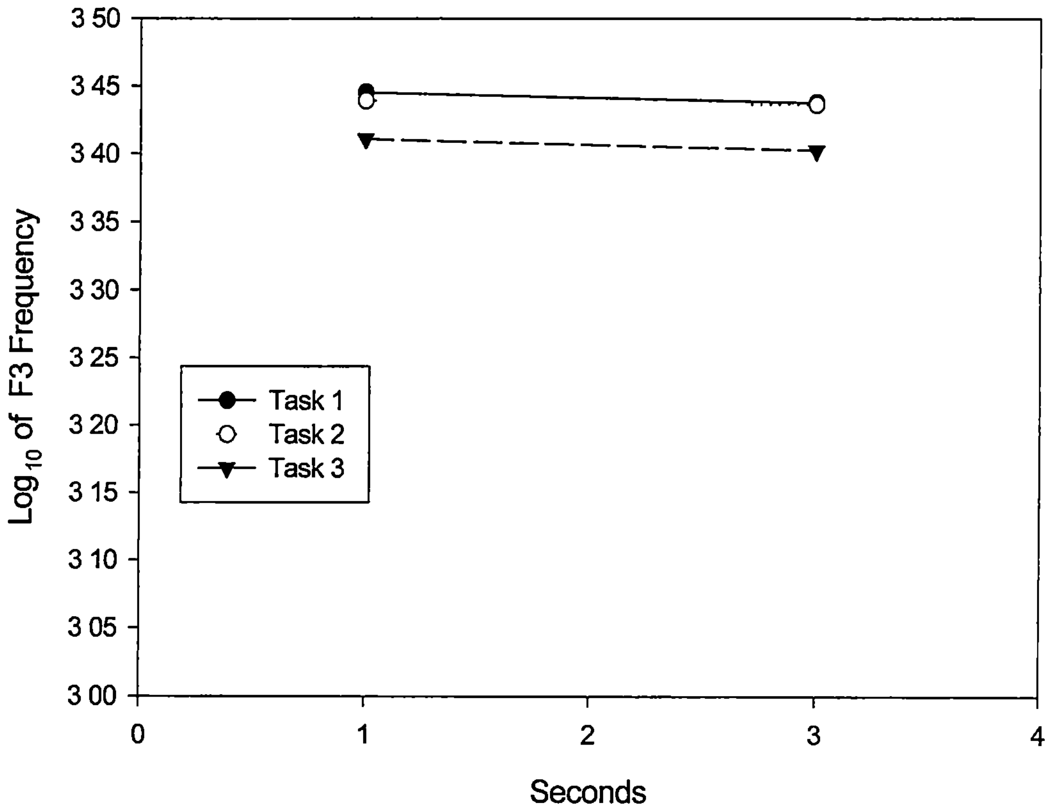

Figure 7: Mean Log10 of F3 formant frequency for the vowel /ɪ/ at second 1 and second 3 on Task 1,Task 2, and Task 3 (n=20)

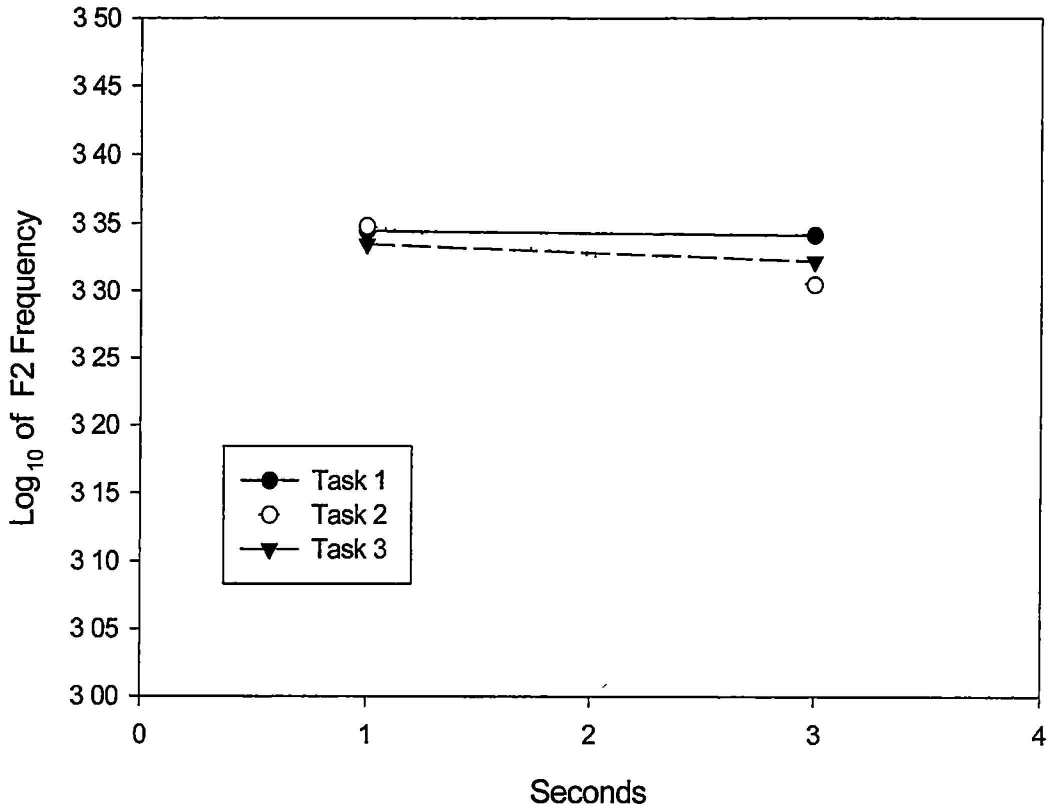

Figure 8: Mean Log10 of F4 formant frequency for the vowel /i/ at second 1 and second 3 on Task 1,Task 2, and Task 3.

Vowel /i/

A strong pattern in the data was seen for F1 and F2 frequencies using artificial laryngeal stimulation with a neck placement. In all post hoc analyses, frequencies for F1 obtained using artificial laryngeal stimulation were significantly higher than those obtained using natural phonation. Likewise, all post hoc analyses revealed significantly lower frequencies for F2 when artificial laryngeal stimulation was compared to natural phonation. Formant frequencies estimated using artificial laryngeal stimulation with an oral insertion differed very little from those obtained during natural phonation for the vowel /i/.

INDIVIDUAL ANALYSES

The second research question sought to determine which method of artificial laryngeal stimulation, neck placement or oral insertion, most accurately measures formant frequency as compared to natural phonation. In order to truly understand the accuracy of these two methods of formant estimation, it was necessary to determine the accuracy of individual formant measurements. In this study, accuracy was determined by calculating percent difference scores between second 1 and second 3 for each vowel, task, and formant. The percent difference scores for task 1, the control task, were used to calculate a 95% confidence interval. Individual percent difference scores for tasks 2 and 3 were then compared to this 95% confidence interval.

Percent Difference Scores

Percent difference scores were calculated for each subject, vowel, formant, and task using equation 2:

$$D_p = (F_{s3} - F_{s1})/F_{s1} * 100 \qquad \textbf{Equation 2}$$

where D_p equals the percent difference score, F_{s3} equals the measured formant frequency at second 3, and F_{s1} equals the measured formant frequency at second 1.

Accuracy Intervals

Confidence intervals for task 1, the control task, were computed. This was accomplished by calculation of the absolute value of D_p for each subject, vowel, and formant. From these absolute values, a 95% confidence interval was computed. This confidence interval served as a control measure against which individual measures from tasks 2 and 3 could be compared. Because percent differences can exceed the 95% confidence interval in both positive and negative directions, an accuracy interval was constructed that could be used to differentiate positive and negative significant differences. Formulas 3 and 4 illustrate the computation of upper and lower boundaries for the accuracy interval

$$AI_u = CI_u \qquad \textbf{Equation 3}$$

$$AI_l = -CI_u \qquad \textbf{Equation 4}$$

where AI_u equals the upper boundary of the accuracy interval, AI_l equals the lower boundary of the accuracy interval, and CI_u equals the upper boundary of the 95% confidence interval.

Individual percent differences for tasks 2 and 3 are graphically compared to accuracy intervals for each vowel and formant in Figures 9 through 16. The top horizontal line on each graph represents the upper bound of the accuracy interval, while the bottom horizontal line on each graph represents the lower bound of the accuracy

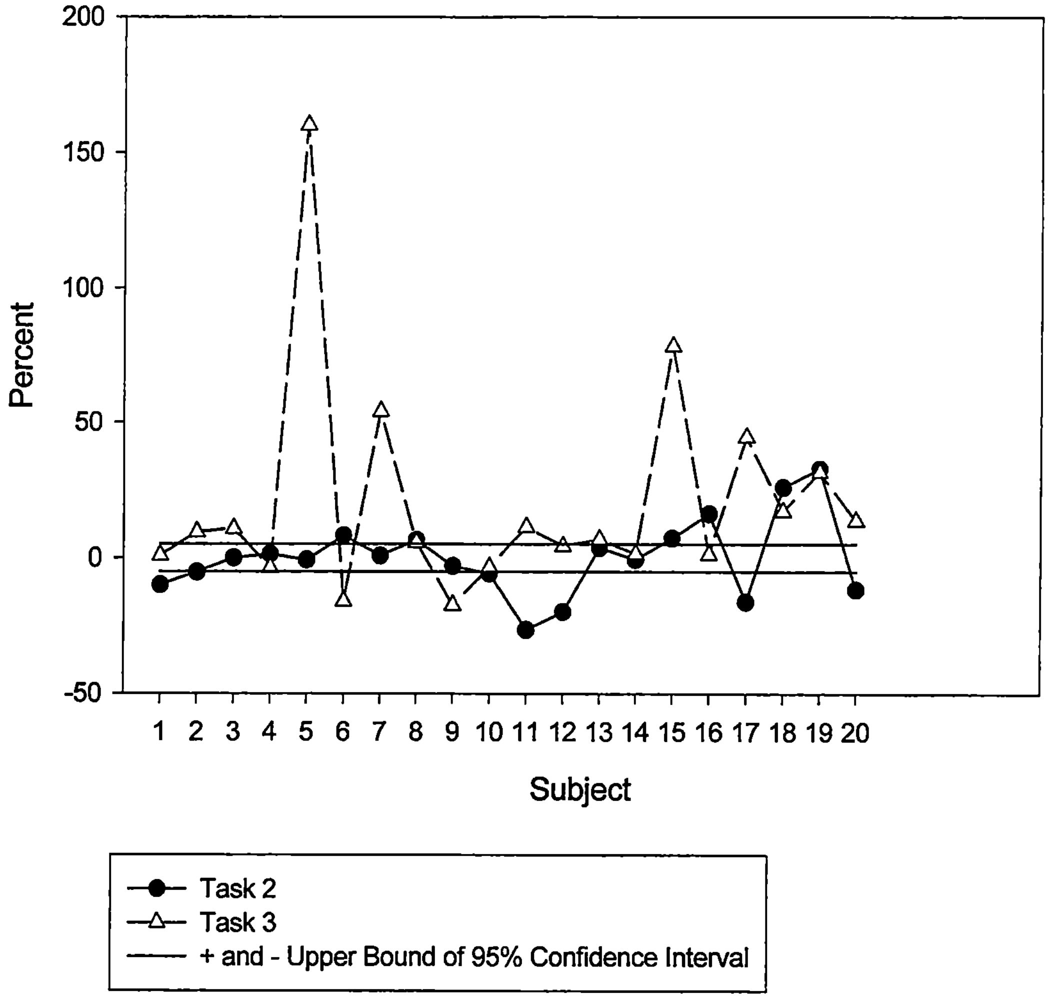

Figure 9: Percent change in F1 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɑ/ on Task 1.

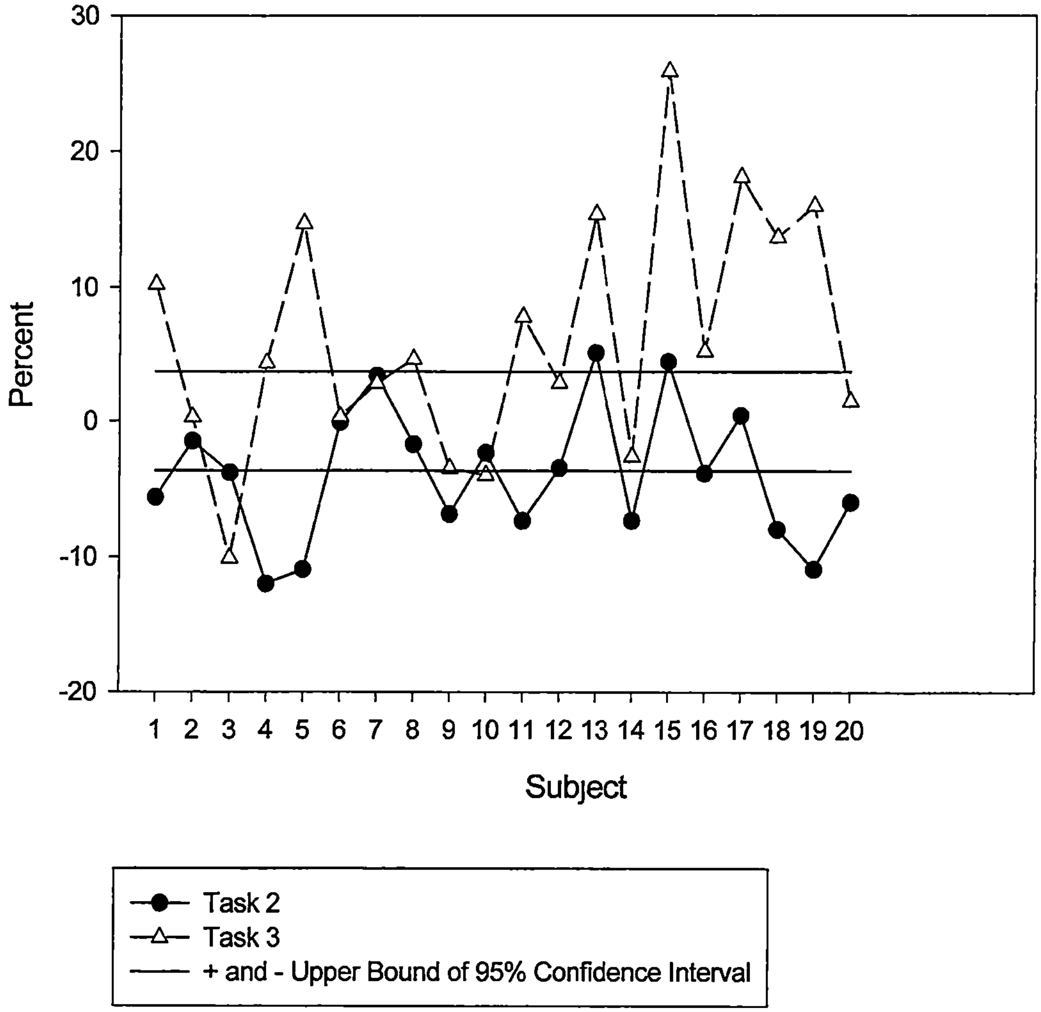

Figure 10: Percent change in F2 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɑ/ on Task 1.

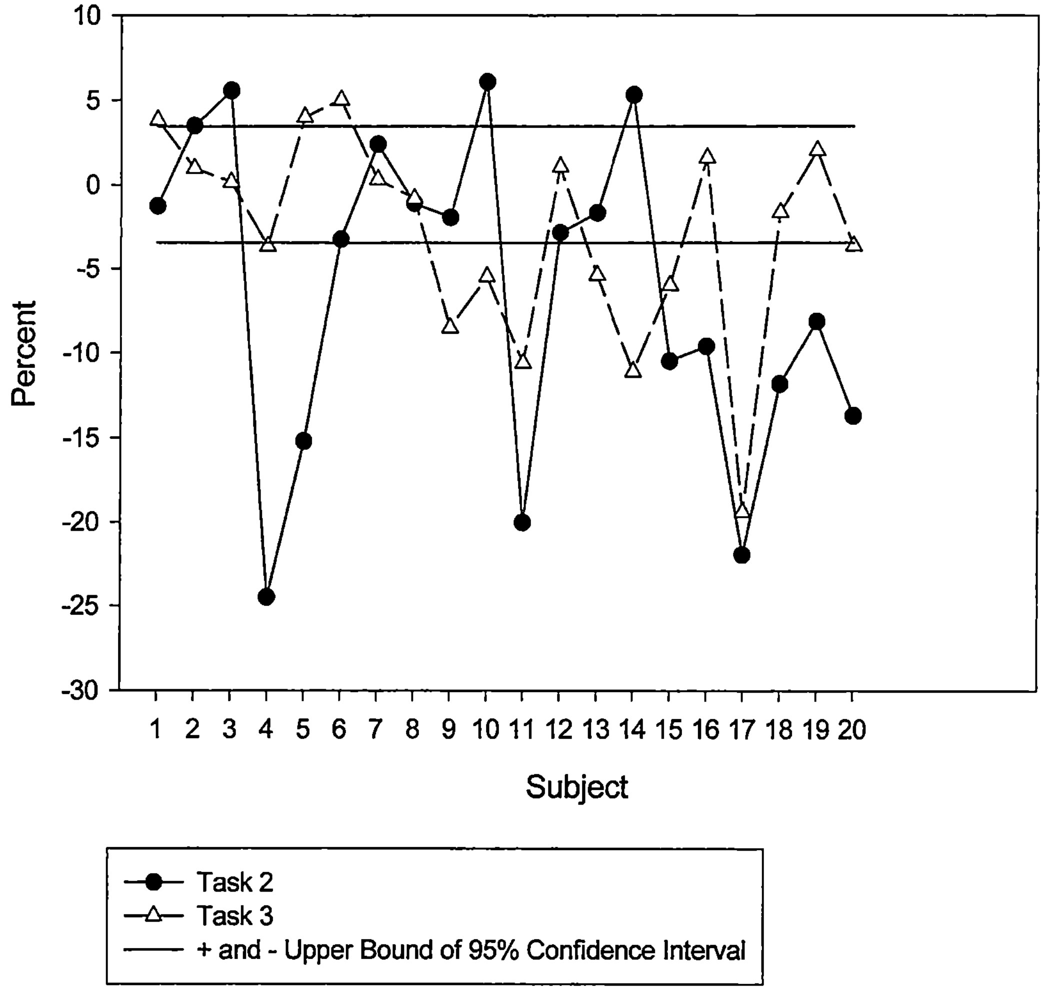

Figure 11: Percent change in F3 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɑ/ on Task 1.

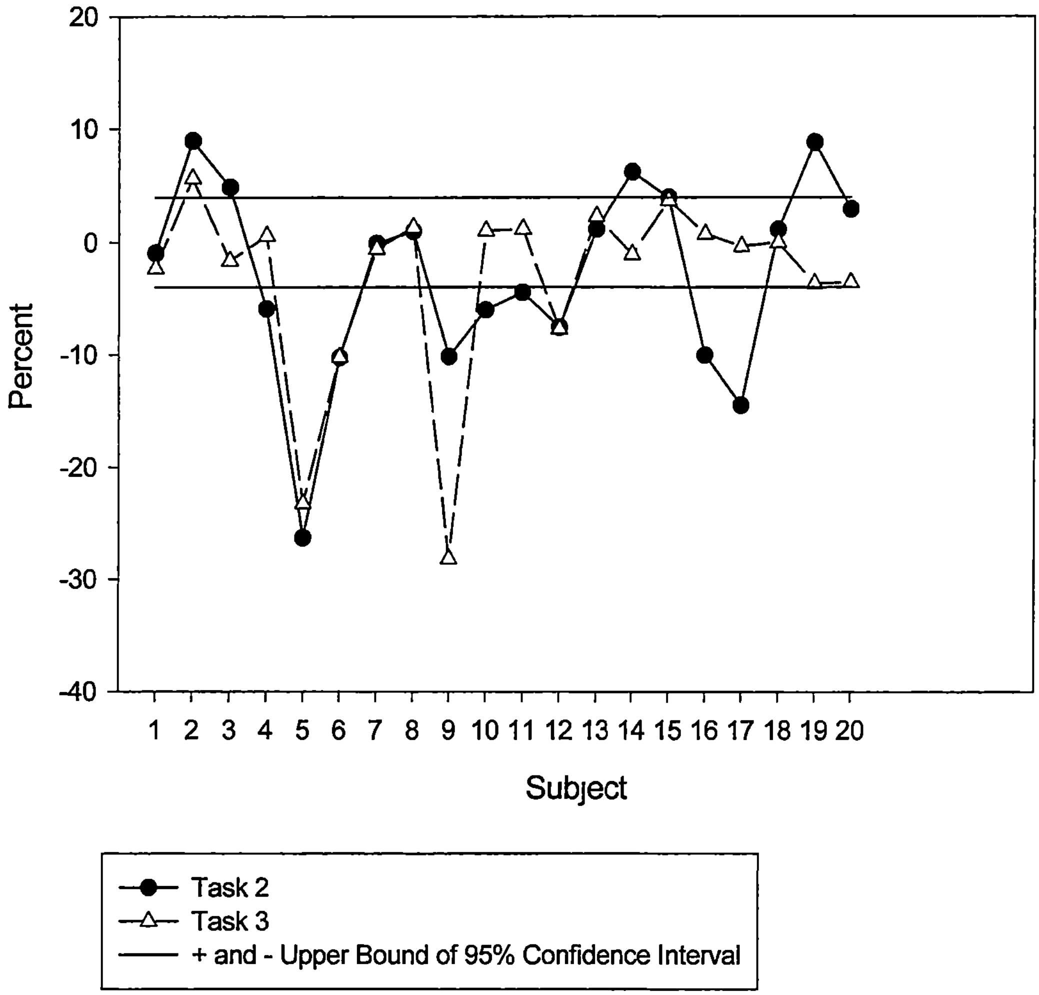

Figure 12: Percent change in F4 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɑ/ on Task 1

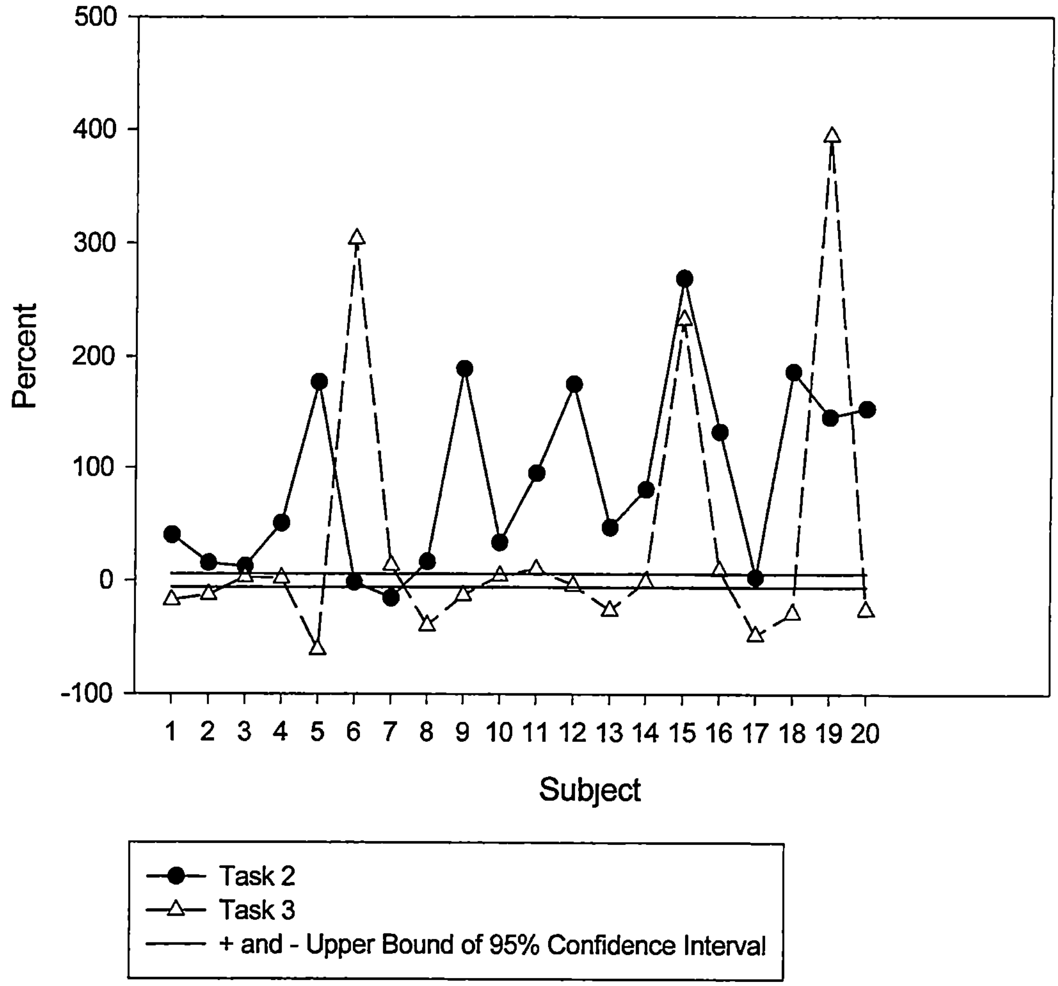

Figure 13: Percent change in F1 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɪ/ on Task 1.

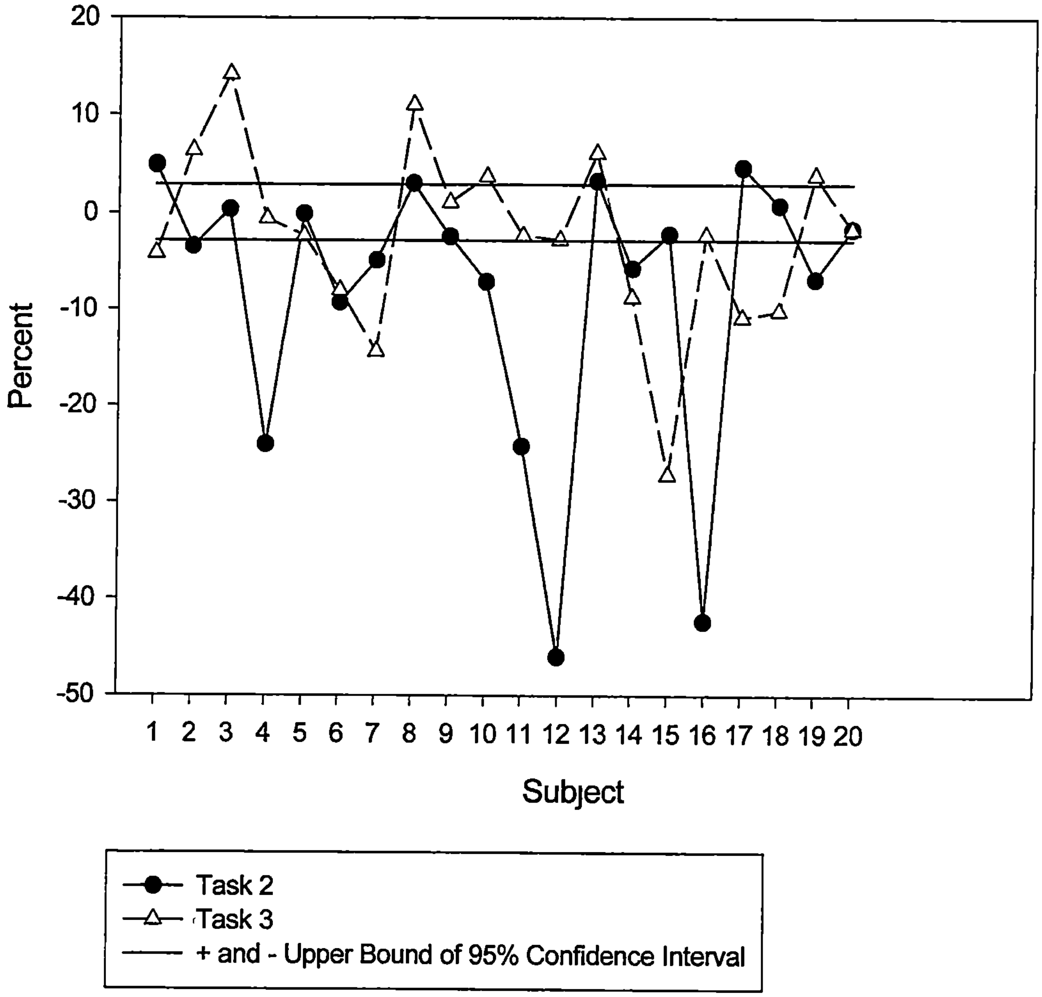

Figure 14: Percent change in F2 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /i/ on Task 1.

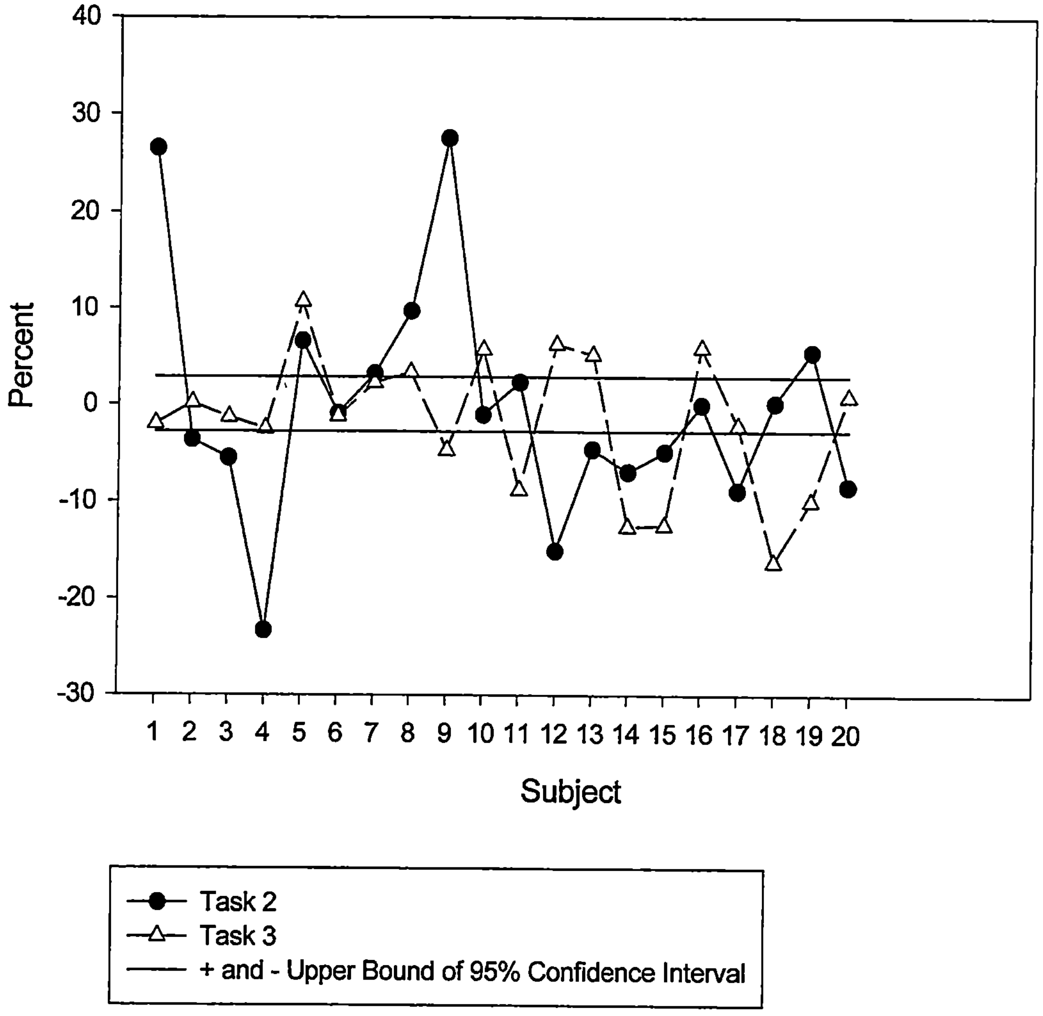

Figure 15: Percent change in F3 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɪ/ on Task 1.

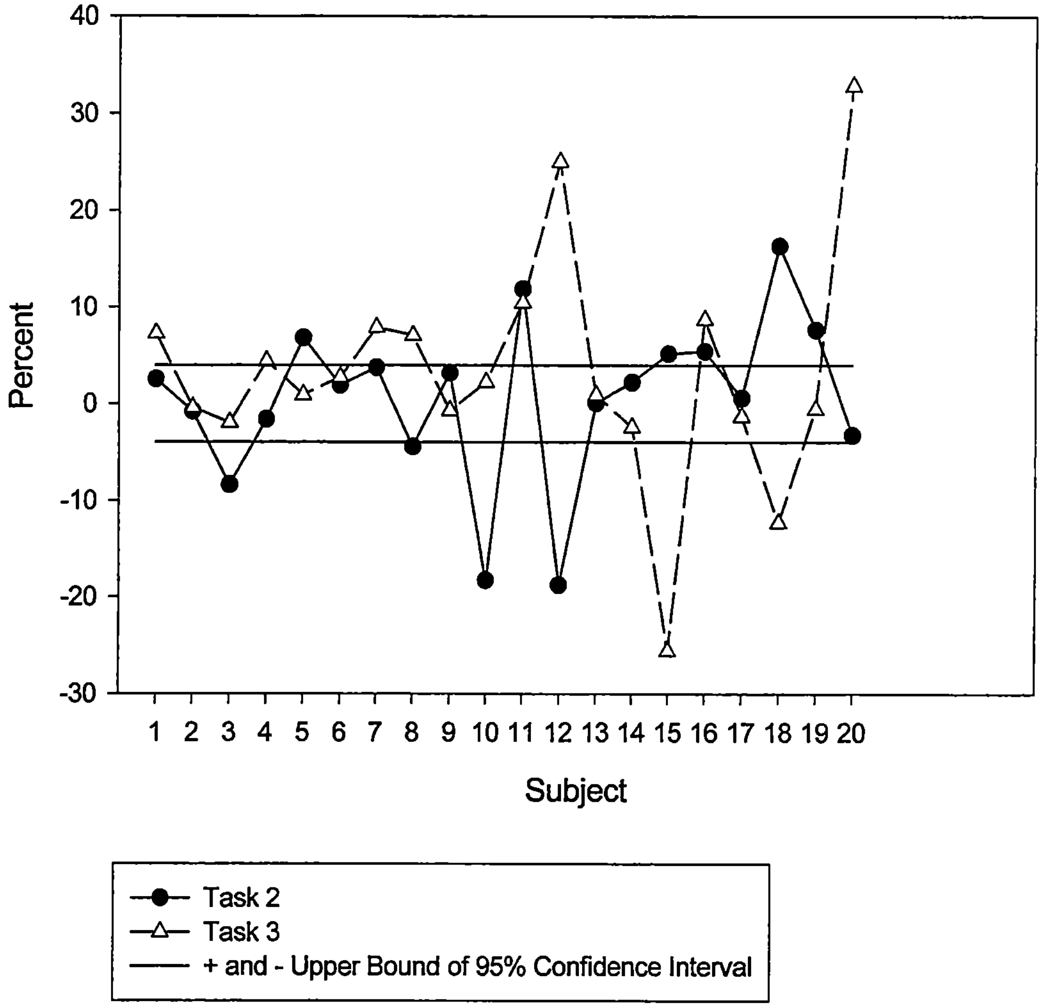

Figure 16: Percent change in F4 formant frequency from second 1 to second 3 for Tasks 2 and 3 as compared to the 95% confidence interval for the vowel /ɪ/ on Task 1

interval. Percent difference scores that exceed the upper bound of the accuracy interval indicate a significant increase in formant frequency from second 1, natural phonation, to second 3, artificial laryngeal stimulation. Percent difference scores that are less than the lower bound of the accuracy interval indicate a significant decrease in formant frequency from second 1, natural phonation, to second 3, artificial laryngeal stimulation

Inaccuracy Measures

Formant measurements for second 3 of tasks 2 and 3 were evaluated for inaccuracy. A formant measurement was considered to be inaccurate if its percent difference score, D_p, did not fall within the accuracy interval for its vowel and formant Thus, a formant measurement was considered inaccurate if it's percent difference score satisfied one of the two equations below:

$$D_p > AI_u \qquad \textbf{Equation 5}$$

$$D_p < AI_L \qquad \textbf{Equation 6}$$

For vowel, task, and formant, the total number of inaccuracies was calculated. This measure was converted in to a percent inaccuracy score using the following equation:

$$I_P = N_I/N_S * 100 \qquad \textbf{Equation 7}$$

where I_P equals the percent inaccuracy, N_I equals the total number of inaccuracies, and N_S equals the total number of subjects Two additional measures were computed, percent positive inaccuracy, I_{PP}, and percent negative inaccuracy, I_{PN}. These measures were computed as follows:

$$I_{PP} = N_{IP}/N_S * 100 \qquad \textbf{Equation 8}$$

$$I_{PN} = N_{IN}/N_S * 100 \qquad \textbf{Equation 9}$$

where N_{IP} equals the number of positive inaccuracies and = N_{IN} equals the number of negative inaccuracies. Results from these analyses for /ɑ/ and /i/ are presented in Tables 9 and 10, respectively.

According to the individual analyses, both methods of artificial laryngeal stimulation produce highly inaccurate formant frequency estimations. The only formant frequency estimation to achieve less than 50% inaccuracy (25%) was F4 for task3, oral insertion, on the vowel /ɑ/. The least accurate formant estimations were obtained during task 2, artificial laryngeal stimulation with a neck placement, for the vowel /i/ Ninety percent of the formant frequency estimations were significantly inaccurate for F1 on this task. Sixty –five percent of these estimations were inaccurate for F2. Seventy-five percent of the formant frequency estimations were inaccurate for F3, while 50 percent of the estimations were inaccurate for F4.

Summary of Individual Analyses

Individual analyses revealed that both methods of artificial laryngeal stimulation, neck placement and oral insertion, were inaccurate predictors of formant frequencies when individual measures were compared to confidence interval computed from the control task, natural phonation, regardless of vowel.

SUMMARY OF RESULTS

Overall, the data suggest that artificial laryngeal stimulation yields formant frequency measurements that differ from those obtained using natural phonation. While

Table 9

Percent Inaccuracy Measures per Task and Formant for the Vowel /ɑ/ (N = 20)

	Percent Inaccuracy							
	Task 2				Task 3			
	F1	F2	F3	F4	F1	F2	F3	F4
Percent Inaccuracy	55%	55%	60%	65%	70%	65%	60%	25%
Percent Positive Inaccuracy	30%	10%	15%	20%	60%	55%	15%	5%
Percent Negative Inaccuracy	25%	45%	45%	45%	10%	10%	45%	20%

Table 10

Percent Inaccuracy Measures per Task and Formant for the Vowel /i/ (N = 20)

	Percent Inaccuracy							
	Task 2				Task 3			
	F1	F2	F3	F4	F1	F2	F3	F4
Percent Inaccuracy	90%	65%	75%	50%	75%	65%	60%	50%
Percent Positive Inaccuracy	85%	15%	30%	30%	30%	30%	30%	40%
Percent Negative Inaccuracy	5%	50%	45%	20%	45%	35%	30%	10%

specific patterns of difference can be observed based on vowel, formant, and task, both tasks, neck placement and oral insertion, performed poorly. Analysis of group and individual data reveal the following patterns of measurement inaccuracy.

Vowel /a/

For the vowel /a/, both group and individual analyses suggest that F2 and F3 formant measurements are significantly lower when using artificial laryngeal stimulation with a neck placement as compared to natural phonation. In contrast, using artificial laryngeal stimulation with an oral insertion elicited consistently higher F1 values than were obtained using natural phonation.

Vowel /i/

As compared to natural phonation on the vowel /i/, artificial laryngeal stimulation with a neck placement yielded formant frequencies for F1 that were significantly higher, while those for F2 were significantly lower. Group analyses indicated that formant frequencies elicited using artificial laryngeal stimulation with an oral insertion did not differ much from those measured from natural phonation; however, examination of individual measurements revealed less than 50% accuracy of estimation for all formants on this task.

CHAPTER FOUR

DISCUSSION

The purpose of this study was to test the accuracy of two formant frequency estimation techniques. This was accomplished by comparing a control task, natural phonation, to two estimation techniques using artificial laryngeal stimulation. The first estimation technique used artificial laryngeal stimulation with a neck placement. The second technique used artificial laryngeal stimulation with an oral insertion. Tasks were performed on /ɑ/ and /i/.

Overall, the methods of formant estimation were not accurate predictors of formant frequencies as compared to natural phonation The accuracy of the particular method, regardless of vowel, varied depending on the formant frequency being measured.

EFFECTS OF ARTIFICIAL LARYNGEAL STIMULATION

Laryngeal Movement

Perturbation theory predicts that formant frequencies are directly related to vocal tract length (Kent and Read, 1992). According to Fant (1970) the longer the length of the vocal tract, the lower the formant frequencies. Therefore, any raising or lowering of the larynx would cause raising or lower for all formants; however, because frequencies of F1 and F2 are also affected by tongue movement, these frequency shifts are most noticeable in F3 and F4.

If formant position were being altered during vowel production using artificial laryngeal stimulation, corresponding changes should be evident in both F3 and F4.

Generally, this was not the case for these data, with one exception. F3 and F4 frequencies were lower during artificial laryngeal stimulation with a neck placement than it was during natural phonation, suggesting a downward movement of the larynx on this task. In all other comparisons, F4 frequency was the most stable measurement across both vowels for all tasks.

Tongue Movement

Tongue advancement and height play a significant role in the perception of vowels in English (Rakerd and Verbrugge, 1985). According to Kent and Read (1992), the frequency of F1 varies inversely with tongue height for a given vowel, while the frequency of F2 varies with tongue advancement. Thus high vowels have low F1 frequencies and low vowels have high F1 frequencies. Likewise, front vowels have high F2 frequencies, while vowels that are farther back have low F2 frequencies. Since one possible source of measurement error in the artificial laryngeal stimulation tasks could be unintentional tongue movement, patterns of movement for F1 and F2 must be analyzed.

It might be expected that task 3, artificial laryngeal stimulation with an oral insertion, would induce unwanted tongue movement due to the invasiveness of the procedure, particularly for the vowel /i/. Specifically, a downward and backward movement of the tongue would be expected, resulting in a raising of F1 frequency and a lowering of F2 frequency. Surprisingly, such changes in both F1 and F2 frequency were not observed on this invasive task for either vowel. Exactly such a pattern was consistently observed, however, for task 2, artificial laryngeal stimulation with a neck placement for the vowel /i/. Mean F1 frequency during this task was nearly double that obtained during natural phonation (531 Hz compared to 285 Hz, respectively), while mean F2 frequency was approximately 8.5% lower than that obtained during natural phonation (2041 Hz compared to 2230 Hz, respectively). It appears that subjects were not able to hold the extreme position for this vowel while changing from phonation to artificial laryngeal stimulation Instead, the vowel became reduced, moving toward the neutral vowel /ə/.

Tracheal Coupling

Tracheal coupling introduces unwanted resonances and anti-resonances into the output speech wave. Signs of tracheal coupling include missing F1 due to severe reduction of F1 amplitude (Coleman, 1976), increased F1 bandwidth (Klatt and Klatt, 1990), and increased F2 frequency (Coleman, 1976). It was hypothesized that tracheal coupling might occur during task 2, artificial laryngeal stimulation with a neck placement, since the vocal folds were not vibrating during this task. However, all subjects were instructed to hold their breath during this task in an attempt to minimize this problem. These instructions appear to have been successful. There were no instances of missing F1 measurements and F2 did not increase significantly for this task as compared to natural phonation.

Summary

The effects of artificial laryngeal stimulation did not appear to be greatly influenced by either laryngeal movement or tracheal coupling. Tongue movement appeared to be the main effect on differences observed in formant frequency estimation

TEST OF HYPOTHESES

It was hypothesized that overall differences would be observed between formant frequencies obtained through artificial laryngeal stimulation and those obtained using natural phonation. It was also hypothesized that artificial laryngeal stimulation with an oral insertion would provide better estimates of formant frequencies than those obtained with a neck placement.

When group data are analyzed, artificial laryngeal stimulation appears to yield significantly different formant values for task 2, artificial laryngeal stimulation with neck placement, as compared to natural phonation. Group data indicate that task 3, artificial laryngeal stimulation with an oral insertion, provides a more accurate estimate of formant frequency as compared to those obtained during natural phonation. Analysis of individual formant measurements for both tasks, however, reveal inaccuracy percentages in excess of 50% for all but one measurement, F4, task 3 for the vowel /ɑ/,suggesting that neither method is an accurate predictor of formant frequency It should be noted, however, that most accuracy intervals calculated in this study were far narrower than the $\pm$ 6% error used in other such studies (e.g., Miller, 1997).

Unfortunately, statistical significance does not necessarily imply practical significance. For example, a statistically significant difference may not necessarily result in a perceptual salient difference. Flanagan (1955) calculated difference limens for various frequencies of F1 and F2. These limens vary greatly depending on the frequency of the formant and the direction of change. For F1, these limens ranged from 3% to 6% For F2, the difference limens varied from 1% to 20% A detailed analysis of individual formant variation as compared to the appropriate difference limen is beyond the scope of this paper. However, examination of difference in F1 frequency between natural phonation and artificial laryngeal stimulation reveal changes in excess of 15% for all conditions but one, artificial laryngeal stimulation with a neck placement for the vowel /ɑ/. Such differences are well beyond the reported difference limens for F1, suggesting that, at least for F1, these formant frequency difference are perceptually significant.

Also, a statistically significant difference at the acoustic level, may not reflect significant differences in physiology. However, Miller et. al (1997) compared acoustic data to spatial dimensions of the vocal tract and found that relatively small changes in acoustic output resulted from rather distinct changes in vocal tract shape and size.

Summary

This study has shown that neither method of artificial laryngeal stimulation, neck placement or oral insertion, accurately predicts formant frequency. The results are believed to be significant at the perceptual and physiological level.

PRACTICAL IMPLICATIONS

Acoustic analysis is the key to studying the vocal folds non-invasively. The acoustic characteristics of the filter provide information about the vocal tract shape and size, while the acoustic characteristics of vocal fold vibration provide information about the vocal fold physiology (Fant, 1970). In order understand vocal fold physiology through acoustic measures, accurate formant frequency measurements are necessary. At this time, such measurements are impossible in high-pitched voices because of the wide spacing of harmonics. Researchers have long advocated use of an artificial laryngeal source as a solution to this problem.

This study represents a first effort to test the effectiveness of two methods of artificial laryngeal stimulation. This study has shown that, as currently implemented, neither method obtains the accuracy necessary for use in research.

METHODOLOGICAL CONSIDERATIONS

Limitations of the Study

Limited Training

This study was limited by the small amount of time and insufficient training with the subjects. Subjects were scheduled for thirty-minute sessions. Many subjects had great difficulty keeping their oral structure in the same position for the control task and the experimental tasks. Perhaps if there had been a longer amount of time to for practice, greater accuracy could have been achieved. Also if the subjects could have come for more than one session, they could have had practice sessions before the method was actually tested. It might have been beneficial if the subjects had come for several practice sessions during which they were recorded. Subsequent recordings could then have been compared with previous recordings to determine whether training increases accuracy.

Lack of Physiological Data

While acoustic data can provide an indication of vocal tract and oral cavity physiology, they cannot be used to definitively determine changes in size and shape of these structures. Since this study was not able to include physiological measures, the results need to be interpreted carefully. Certainly, it is possible to judge accuracy of formant estimation from the acoustic data collected in this study. It is the physiological interpretation of these acoustic inaccuracies that must be evaluated cautiously.

Strengths of the Study

One strength of this study was the number of comparisons that were made There were two methods of formant frequency estimation, comparing four formant frequencies on two vowels measured at two points in time A second strength was the use of a 95% confidence interval obtained from a control task

Comparisons

Formant frequency estimation was compared across tasks as well as across time. This provided a nice two-way comparison in which the two experimental tasks could be compared to the control task as well as to natural phonation on the same task

Formant Frequency Estimation

Using two methods of formant frequency estimation allowed differences between the methods to be evaluated. Furthermore, the differences between the methods served as a control for each other. For example, in task three the vocal folds continued to vibrate which controlled for trachea coupling. At the same time, the neck placement used on task 2 allowed for the subject to produce the vowel without interference of the orally placed tube.

Formant Frequencies

Measuring four formants is beneficial in that it aids in the identification of what is happening anatomically in the vocal tract without physically manipulating or invading these structures. When expensive medical equipment is not available for studying the structures contained in the vocal filter, information about these structures can only be obtained via the directional movement of the four individual formant frequencies.

Two vowels

Comparing two vowels on the same tasks will be helpful in future research The use of two vowels was an advantage because it demonstrated which vowel yields more accurate formant frequency estimations under specific conditions.

95% Confidence Interval

This study was greatly enhanced by the research design. Previous research has used ± 6% as a standard of for formant frequency estimation (Miller, 1997). This study differs from previous research in that the control task was used to calculate a 95% confidence interval, to which the individual formant frequency measures on the two experimental tasks could be compared. Thus, the standards used in this study impose stricter constraints than those used in previous designs.

IMPLICATIONS FOR FUTURE RESEARCH

Future research should be conducted wherein training sessions are implemented for each subject to practice both tasks. Perhaps the methods of formant frequency estimation would produce accurate formant frequencies if the subjects were more familiar with the apparatus.

Other methods of formant frequency estimation should be evaluated. A possible task that may produce more accurate formant frequency estimations would be a combination of the two used in this study Subjects could be required to use the artificial larynx placed on the neck while continuing to vibrate the vocal folds This would eliminate tracheal coupling and perhaps steady the position of the oral cavity structures. Because of the intensity of the new Servox artificial larynx this method of formant frequency estimation is made possible.

A final implication for future research on this topic would be to make between-group comparisons of trained vs. untrained individuals Trained subjects could have a musical, acoustical, or voice background. Trained subjects may be more likely to hold vocal structures in a sustained position than would those with no vocal training

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

SUMMARY

The first hypothesis stated that there would be overall differences in formant frequency estimations between those obtained via natural phonation and those via artificial laryngeal stimulation. Significant differences were seen in formant frequencies based on time, task, and formant.

The second hypothesis stated that artificial laryngeal stimulation via oral insertion would yield more accurate formant frequencies than those estimated through use of artificial laryngeal stimulation via neck placement While task 3, oral insertion, did appear to be more accurate than task 2, neck placement, on the group analyses, when looking at the individual analyses, inaccuracy percentages in excess of 50% for all but one formant were revealed. Therefore, oral insertion was not significantly more accurate than neck placement. In fact, neither method produced accurate formant frequency estimations on any formant.

CONCLUSIONS

In conclusion, neither of the methods of formant frequency estimation tested in this study yielded accurate formant frequencies for all formants. This is apparent at the perceptual level as well as at the physiological level. Unfortunately the acoustic monster has not been defeated and the difficulty in estimating formant frequencies in high-pitched voices still remains. Until further research is performed on this topic, the formant frequencies predicted via these methods of elicitation may not be accurate.

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APPENDICES

APPENDIX A: RAW FORMANT FREQUENCY MEASUREMENTS

Raw Formant Frequency Data in Hertz for Task 1 for the Vowel /ɑ/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	797	1258	2611	3558	828	1321	2653	3606
2	640	1185	2387	3377	642	1194	2390	2971
3	665	1346	2445	3605	683	1342	2373	3550
4	713	1156	2669	3322	755	1146	2764	3402
5	786	1233	2437	3989	815	1127	2409	3954
6	663	1275	2718	3581	598	1226	2661	3540
7	539	1217	2427	3762	580	1222	2489	3718
8	701	1153	2527	3396	666	1105	2601	3394
9	814	1316	2687	3721	736	1228	2730	3679
10	762	1166	2573	3258	761	1207	2495	3254
11	679	1165	2504	3153	664	1192	2600	3379
12	707	1245	2425	3557	688	1252	2209	3485
13	610	1054	2528	3645	605	1054	2541	3665
14	788	1381	2655	3484	766	1291	2599	3471
15	477	999	2277	3426	508	1008	2190	3317
16	637	1061	2260	3272	615	1060	2278	3488
17	617	1040	2740	3369	621	1032	2792	3369
18	666	1094	2581	3571	658	1098	2529	3728
19	636	1078	2618	3565	655	1091	2528	3717
20	729	1266	2635	3504	736	1298	2558	3501

Raw Formant Frequency Data in Hertz for Task 2 for the Vowel /ɑ/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	773	1294	2585	3496	696	1221	2552	3463
2	653	1190	2489	3105	619	1172	2576	3381
3	680	1073	2275	3521	680	1032	2402	3692
4	780	1174	2784	3416	791	1033	2102	3214
5	715	1160	2754	3953	709	1033	2335	2915
6	655	1183	2393	3350	708	1181	2315	3005
7	616	1203	2448	3703	620	1244	2507	3699
8	745	1172	2445	3433	793	1152	2418	3467
9	717	1226	2473	3627	695	1142	2425	3259
10	754	1195	2527	3202	711	1167	2681	3010
11	721	1137	2682	3258	530	1053	2145	3114
12	774	1171	2594	3719	620	1131	2520	3438
13	641	1013	2576	3443	665	1065	2533	3484
14	768	1329	2647	3383	763	1232	2787	3592
15	509	971	2498	3507	546	1014	2236	3646
16	650	1067	2455	3269	755	1026	2218	2940
17	720	981	2777	3195	603	985	2167	2732
18	662	1046	2659	3764	833	963	2344	3806
19	664	1051	2557	3553	882	937	2348	3864
20	704	1259	2579	3471	622	1183	2225	3572

Raw Formant Frequency Data in Hertz for Task 3 for the Vowel /ɑ/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	785	1166	2638	3598	792	1285	2739	3515
2	650	1223	2406	3306	711	1227	2429	3492
3	709	1210	2407	3603	785	1088	2411	3545
4	758	1094	2665	3256	731	1142	2568	3275
5	409	1027	2384	3608	1063	1178	2480	2771
6	661	1209	2222	3173	556	1213	2334	2849
7	603	1162	2543	3542	929	1194	2551	3522
8	715	1117	2377	3263	755	1169	2358	3307
9	831	1265	2671	3833	686	1221	2443	2754
10	816	1194	2320	3146	788	1147	2193	3179
11	678	1086	2816	3218	755	1170	2516	3256
12	714	1177	2387	3900	745	1210	2412	3598
13	654	1034	2493	3267	699	1193	2358	3342
14	808	1280	2647	3294	819	1246	2353	3258
15	565	1009	2547	3442	1007	1270	2395	3569
16	711	1097	2320	3470	720	1154	2357	3495
17	628	1001	2930	3316	908	1182	2362	3304
18	676	1055	2521	3580	792	1199	2480	3580
19	644	1026	2443	3662	848	1191	2493	3529
20	742	1205	2731	3621	843	1223	2632	3492

Raw Formant Frequency Data in Hertz for Task 1 for the Vowel /i/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	281	2189	2653	3347	279	2122	2610	3336
2	332	2183	2717	3616	317	2161	2622	3587
3	251	1954	2894	3441	255	2014	2882	3381
4	259	2233	2795	3556	282	2169	2818	3115
5	263	2207	3062	3463	264	2045	2984	3408
6	262	2205	2623	3452	271	2220	2544	3153
7	287	2113	2698	3374	343	2078	2631	3496
8	313	2237	2516	3079	305	2271	2467	3074
9	314	2333	3021	3564	326	2305	2860	3629
10	365	2391	2932	3550	359	2352	2912	3521
11	254	2269	3087	3441	251	2282	3078	3375
12	227	2460	3050	3520	233	2482	3107	3346
13	300	2113	2636	3471	305	2055	2575	3524
14	299	2419	2994	3579	297	2395	2920	3542
15	263	2089	2634	3315	256	2097	2551	3317
16	316	2131	2657	3487	310	2243	2662	3421
17	256	2095	2537	3280	263	2049	2470	3363
18	242	2227	2625	3270	264	2237	2586	3198
19	306	2035	2887	3647	304	2012	2738	3578
20	309	2365	2855	3546	288	2308	2885	3579

Raw Formant Frequency Data ın Hertz for Task 2 for the Vowel /i/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	259	2218	2697	3330	363	2326	3412	3412
2	321	2314	2795	3622	370	2234	2693	3593
3	257	2043	2828	4040	289	2050	2671	3701
4	255	2160	2884	3687	383	1640	2212	3627
5	248	2220	3018	3465	687	2217	3217	3699
6	280	2337	2615	3284	276	2119	2590	3346
7	346	2062	2698	3588	293	1960	2784	3721
8	355	2202	2514	2886	413	2268	2758	2758
9	331	2222	2655	3646	956	2168	3387	3761
10	358	2364	2918	3534	477	2195	2886	2886
11	261	2301	2960	3232	509	1744	3027	3615
12	227	2368	2556	3477	625	1278	2172	2824
13	291	2107	2769	3555	428	2175	2640	3556
14	287	2412	3034	3505	518	2273	2823	3581
15	262	2024	2558	3291	968	1978	2432	3460
16	315	2341	2371	3196	731	1350	2369	3368
17	269	2194	2885	3397	278	2296	2629	3416
18	266	2324	2633	3241	760	2341	2636	3769
19	264	2076	2815	3453	648	1933	2969	3715
20	260	2316	2887	3573	658	2277	2644	3456

Raw Formant Frequency Data in Hertz for Task 3 for the Vowel /ɪ/

Subject	Second 1				Second 3			
	F1	F2	F3	F4	F1	F2	F3	F4
1	292	2208	2600	3289	242	2116	2546	3526
2	331	2026	2700	3552	289	2155	2703	3537
3	288	2016	2624	3579	296	2301	2588	3508
4	291	2176	2594	3377	296	2162	2528	3524
5	309	2000	2166	3445	121	1952	2398	3474
6	314	2131	2446	3217	1269	1959	2416	3304
7	338	1957	2330	3160	383	1675	2382	3408
8	359	2091	2318	3487	217	2321	2395	3733
9	324	2308	2789	3415	282	2332	2657	3390
10	368	2212	2690	3542	383	2294	2844	3620
11	245	2271	2758	3026	269	2217	2515	3342
12	232	2265	2584	3650	222	2202	2746	4563
13	335	2123	2434	3595	247	2252	2560	3626
14	307	2520	2939	3393	303	2299	2569	3309
15	281	2096	2659	3359	936	1525	2327	2498
16	315	2264	2453	3161	343	2211	2597	3434
17	258	2175	2479	3392	134	1938	2424	3346
18	302	2070	2775	3731	215	1858	2325	3271
19	254	2184	2937	3409	1257	2267	2644	3388
20	327	2159	2385	3472	242	2122	2403	4612

VITA

Amy Elizabeth Carrubba was born and raised in Clinton, Mississippi She began her undergraduate degree in Speech Pathology at the University of Southern Mississippi (USM) in Hattiesburg in 1994 During her two years at USM she served as the Vice President of the Greek system, received academic honors including the President's list and several honor societies, and was a football and basketball cheerleader.

In the fall of 1996 Amy transferred to the University of Tennessee Knoxville (UTK) where she was a member of many honor societies, was on the Dean's list, served as the Junior Vice-President and Secretary of the National Student Speech Language Hearing Association (NSSLHA), and enjoyed performing at the Clearance Brown Theater. She received her Bachelors of Science degree with honors in Speech-Language Pathology in the spring of 1998.

Amy returned to UTK in the fall of 1998 where she earned her Master of Arts degree in Speech-Language Pathology in the spring of 2000. While working on her masters, she served as the President of NSSLHA and received a graduate assistantship working for Child Hearing Services (CHS).