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The Acoustic Correlates of [ATR] Vowel Harmony in Somali

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by

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Abstract

In the scholarship on the Somali language, lexical and syntactic structures have received disproportionately more attention than phonetic analyses. This study was concerned with the phonetic elements of the language and how they manifest acoustically. The goal of this research was to empirically describe the relationship between tongue root harmony constraints and several other phonetic features of Somali vowels that affect vowel quality in the articulation of selected phonemes. To accomplish this, baseline measurements of the acoustic features of each set of [± ATR] (Advanced Tongue Root) vowel sounds were taken in spectrograms and compared across sets. The measurements made for each waveform include: fundamental frequency, formant 1, formant 2, formant 3 and vowel duration. The values were submitted to independent samples t-tests. The tests indicate that F1 is the most reliable correlate of [ATR] followed by duration. F2 is reliable for some vowel pairs while F3 demonstrated little significance. F0 was not a significant correlate in distinguishing between any vowel pairs.

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Chapter 1: Introduction

Vowel harmony and its manifestation through [ATR] constraints has been examined for many languages. While it is sometimes difficult to define, the impact of vowel harmony within the languages in which it operates can be observed. Somali is one such language. Vowel harmony operates in Somali through the governing of the types of vowels that may appear in a word together. Vowels within a Somali word must be pronounced with the same [ATR] designation: either with an advanced tongue root ([+ATR]) or a retracted (or neutral) ([-ATR]) tongue root. The goal of the present study was to empirically describe the differences between vowels with these contrasting [ATR] features. The fundamental question in this study was: are [ATR] constraints of vowels within a word correlated with other acoustic variations? The goal was to determine the acoustic correlates of [ATR] vowel harmony by establishing the existence of any significant differences in the vowels of nouns and verbs produced in the standard Somali dialect. This task was achieved by measuring several common acoustic variables of vowels against [ATR] and testing the variation for significance. While there are several identifiable manifestations of vowel harmony, the scope of the present study is limited to the role of [ATR].

Ultimately, this research is important in so far as it relates to perceptual differences in speech sounds. It allows us to more carefully distinguish Somali vowels apart acoustically. This aids our understanding of the articulation and auditory perception of vowels by providing an empirical account of the differences in the vowels. Many vowel quality features of Somali are also often unnoticed by researchers or non-native speakers of the language who seek to document information about its linguistic structure. These subtle differences that may go unnoticed by the ear include relative pitch, direction of pitch changes, relative length, and differences in voice quality (Baart, 2010).

Somali Language Overview

Somali, which is classified linguistically as an Afro-Asiatic language is further subdivided as a Cushitic language. More specifically, it can be categorized as East Cushitic in the same way that the Ethiopian languages of Oromo and Afar are classified. The standard dialect in Somali is known as the Isaaqi dialect. It is also sometimes referred to as the Northern dialect. This dialect has historically been used by Somali people as the "Lingua Franca" within Somalia and was used by the most well-known poets and literary figures as well as official government institutions (Saeed, 1999).

The branch of the Somali language that has received the most attention has been the lexicon, and the area that has received the least attention is phonetics and phonology (Saeed, 1999). The seminal studies on Somali phonology are dated as far back as 1934 and some studies on other characteristics of the language were published even earlier. The language as a whole, has received relatively little attention from the linguistic community. Though it is the most studied of the Cushitic languages, much work remains to be done.

Since this study is concerned with measuring and describing the acoustic characteristics of vowels, I will provide only a brief introduction of the consonants followed by a more robust description of the vowel system with respect to the features that are of concern in this study.

Somali Syllable Structure

In Somali, there is a simple syllable structure that is realized as (c) v (c). The full set of possible syllable structures is {V, CV, VC, CVC} where V can vary as a short vowel, long vowel, or diphthong (Saeed, 1999). For this study, acoustic analyses will be carried out on both mono-syllabic and di-syllabic words.

Consonants

According to Saeed (1999) there are twenty-two distinct consonants in the Somali language which are spread across all positions of articulation. Features and places of articulation are exhibited in Table 1 (Koffi, 2010) below.

Table 1

Somali Consonant Chart

	Bilabial	labiodental	Alveolar	Palatoalveolar	Retroflex	Velar	Uvular	Pharyngeal	Glottal
Stops Voiceless			t			k			ʔ
Stops Voiced	b		d		ɖ	g	ɢ		
Fricatives Voiceless		f	s	ʃ			χ	ħ	h
Fricatives Voiced								ʕ	
Affricates Voiceless				ʧ					
Nasals	m		n						
Trill			r						
Lateral					l				
Glides	w			j					

Vowels

While the Somali consonant system has some co-articulatory effects on the vowel system, it is the vowel system that presents the phenomena of interest in this study. Somali has a unique two set system of the traditional five vowel system in which each of the five traditional vowels has an Advanced Tongue Root version and a non-Advanced Tongue Root version (Saeed, 1999). Saeed differentiates these two sets as [+ATR] vowels and [–ATR] vowels. Each vowel can also occur long, though without change in quality so, in total there are twenty potential vowel variations. Table 2 below exhibits the two sets of [+ATR] and [– ATR] vowels distributed across the three possible vowel heights.

Table 2

Somali ATR Vowel Sets grouped for [± High, Low, Mid] feature

Height	[+ATR]	[- ATR]
High	[i, u]	[ɪ, ʊ]
Mid	[e, o]	[ɛ, ɔ]]
Low	[æ]	[ɑ]

The traditional classification of front vowels and back vowels with respect to place of articulation is presented in Table 3 below.

Table 3

Somali Vowels grouped for [±back] feature

Front	Back
[i, ɪ]	[u, ʊ]
[e, ɛ]	[o, ɔ]
[æ]	[ɑ]

Tone vs. Pitch-Accent debate

The question of whether Somali is an intonation, tonal, or pitch-accent language is an interesting and complicated one. Saeed (1999) makes a good distinction by suggesting that Somali does not use pitch to carry sentence level information in the way that English does; “tone is used to make contrasts at the word level” (1999, 23). Hyman (1981) and Banti (1988) suggest a tonal accent system for Somali. In Somali, it is the Mora that receives an accent as opposed to the syllable as it is in many other languages (Saeed, 1999). Andrzejewski (1979) Hyman (1981) and Saeed (1999) all note that, in general, Somali roots themselves do not have tone. Saeed characterizes the application of tone as such:

> "Rules of accent placement determine the position of a single accented mora in each root, which is then phonetically realized as a high pitch segment." (Saeed, 1999,p.24).

Edmondson et al (2004) suggest four tonal features of Somali. First, tones in Somali have either two or three heights as in table 4 below. Second, tone is not governed by rules of vowel harmony. Third, tone carries sentence level information.

Table 4

Assignment of Somali Tones

High Tone	on Short vowels
Low Tone	on short vowels and long vowels and diphthongs
Falling Tone	on long vowels and diphthongs.

(Adopted from Saeed (1999) with omission of accented examples.)

While phonemic tone is an important part of the Somali phonemic inventory, it is not governed by vowel harmony. The tokens used in this study will not reflect a control for high and low tones.

Chapter II: Literature Review

Much of the literature related to this study can be understood in terms of providing 1) theoretical/conceptual information and 2) methodological information. Theoretical studies inform the present study with the concepts and language necessary to address the research questions, and the quantitative studies provide adoptable methods for data collection and analysis.

Descriptive Techniques for Vowels

It is important to note that there is an inherent challenge in describing vowels that leads to a lack of concreteness that we do not find in the descriptions of consonants. The primary source of this difficulty lies in the fact that we cannot clearly identify all the ways in which the tongue moves during the interaction of the multiple articulators employed in the production of vowels (Ladefoged, 2001).

This challenge in describing vowels notwithstanding, there is a generally recognizable format for discussing vowel features in linguistic scholarship that will also be followed in the sections to come and throughout the remainder of this study. Taking an articulatory approach to describing vowels, the quality of a vowel is determined by the general shape and size of the vocal tract as determined by the relative position of the tongue and shape of the lips. There are several ways to describe vowels for phonetic analysis. Amongst the most often used are cavity, vowel height, backness, roundness, expansion, and duration (Lindau, 1978; Ladefoged 2006). The most important features for the analysis of Somali vowels in this study are aperture, backness, expansion, and duration. The first three of the aforementioned features correspond with the feature hierarchy that is discussed by Ladefoged and are the most important features in this study.

These features are contrasted as either high/low, front/back, and expanded or restricted pharynx. Duration is measured in milliseconds. The most important mechanism in describing the expansion feature of vowels is the relative position of the tongue root – either advanced or retracted. This expansion feature has been described as advanced tongue root and retracted tongue root. As a result of this, the expansion feature is noted as [± ATR] and that is the notation that will be used henceforth. Vowel height refers to the opening of the mouth – a smaller opening results in a higher vowel and a bigger opening results in a lower vowel. Vowel backness refers to the tongue movement. In articulating vowels, the tongue may sometimes move forward resulting in front vowels or backward resulting in back vowels. Central vowels are a result of the lack of forward or backward movement.

Acoustic Analysis of Vowels

The inspiration for the methodologies employed in this project can be found in Barney and Peterson's work (1952) in which they describe the types of acoustic measurements that can be taken of vowels in order to draw conclusions about speech sounds produced by individuals. In their study on North American vowels, they emphasize the importance of the calibration of instruments, repeating of selected utterances and the types of frequencies that are important to keep in mind when conducting vowel analysis. Some of the most significant work on acoustic phonetics has been done by Ladefoged (1982; 1996; 2001; 2003). His description of the phonetic distinction between vowels and consonants provides sufficient rationale for the differences in features one must look for when measuring either one – "...a vowel is defined by features that ensure that there are no major strictures in the vocal tract; and that it is syllabic." (Ladefoged,1996, p.281).

When performing acoustic analyses on vowels, there are several things that are traditionally sought: vowel pitch, quality, and amplitude. The pitch of a vowel is also known as the fundamental frequency of a vowel. Quality refers to the combination of the formants produced by an individual for each vowel. When the formants are combined with the different features, it allows for people to distinguish between vowels. Amplitude refers to the loudness of the vowel.

Advanced Tongue Root [ATR]

Historically, [ATR] was known as a minor feature of vowels in comparison to tongue height and backness features. However, recently, its role in vowel quality has gained interest in the realm of acoustic engineering and speech sound analysis. It is essential to understand that simply because the tongue root may be more forward in the production of some vowels does not mean that the vowel is a [+ATR] vowel. Sometimes the movement of the tongue root can be a secondary effect caused by the articulatory mechanism that determines vowel height. In order for a vowel to receive the [+ATR] feature designation, it has to be caused by "an active movement of the tongue root" (Ladefoged, 2007, p.166). Similarly, [-ATR] does not necessarily refer to retraction of the tongue root, but rather the lack of the forward movement of the root.

Scholarship on [ATR] Harmony

[ATR] vowel harmony is found in many languages to different degrees. In some cases, acoustic studies on the phonetic realization of [ATR] harmony have provided empirical evidence. In others, only the phonological features of [ATR] have been studied. [ATR] is believed to operate even in dead languages as old as Sumerian (Smith, 2007) to some degree.

In languages like Somali, Akan, and several other African languages, the ATR feature distinguishes between two sets of vowels. In such languages, the difference between the two sets of vowels is not simply the forward advancement of the tongue root, but rather the entire change in size of “the whole pharyngeal cavity, partly by the movement of the tongue root, but also by the lowering of the larynx”(Ladefoged,1982:74). Using x-ray cinematography, Ladefoged shows that “there is a noticeable difference in the bandwidths of the formants” that shows narrower bandwidths in [+ATR] vowels which can be explained by the “greater tension of the vocal tract” (1982:74).

Studies on the acoustic correlates of [ATR] harmony for African languages have focused on West African languages. The methods used in this paper are inspired by such studies. [ATR] harmony does not always operate in the same way and does not always reflect the same acoustic correlates. For example, [ATR] harmony is not always progressive, applying from left to right within the boundary of a word. It is sometimes the case that there are regressive harmonic effects from vowels in the secondary position onto vowels that come first in a word. In a study on a northern language of Ghana, Kwa, there were more regressive [ATR] effects observed than progressive (Casali, 2002). In Somali, lexical suffixes regressively harmonize other vowels in the root word while in some cases the root word vowels progressively harmonize the vowels in the suffixes. In another study on a Nilo-Saharan language, [ATR] effects were found to be correlated with vowel height contrasts and durational contrasts (Guion, Payne & Post, 2004).

From such studies, it has been found that the first formant is the most reliable acoustic correlate for ATR harmony in some African languages (Starwalt, 2008; Anderson, 2007). It is not the case that vowels in each set of harmony pairs always share the same acoustic correlates and/or exhibit them to the same degree. In a study on seven and nine vowel African vowel harmony languages Starwalt (2008) found that while for some languages F1 was the main acoustic correlate of ATR, F2 failed to show a statistically significant effect. Examples of these languages from Starwalt's study are the two Yoruba dialects Ekiti and Moba and two other West African languages - Ikposo and Foodo. However, from the same study, F2 means reliably distinguish between [ATR] vowels for the languages of Kinande and LuBwisi. Similarly, Koffi (2016) found that F1 was the most reliable correlate while F2 failed to distinguish between [ATR] pairs in Anyi.

As mentioned above, scholarship on [ATR] vowel harmony is not limited to just African languages. In a study of French vowel harmony, it was found that in addition to vowel height variations, [ATR] was related to backness variation as well (Nguyen and Fagyal, 2008).

One of the most relevant research results to this study are from a study done by Edmondson, Elsing and Haris (2004) in which acoustic and laryngoscopic analyses were performed on the pronunciations of one Somali speaker. The results showed that [+ATR] vowels seem to be more fronted and higher than their counterparts in general.

In the present study, an acoustic analysis was performed on eight speakers accounting for measurements of the first three formants, vowel duration, and fundamental frequency to provide a more robust acoustic analysis on the correlates of [ATR] in Somali. Ultimately, the goal was to determine if there are statistically significant differences in the mean values of the selected acoustic features between the phonemes in each [ATR] pair.

Vowel Harmony

Harmony, a phonological process, is well documented for many languages. It has been shown to exist for both consonants and vowels. It is defined as a "phonological assimilation for harmonic feature(s) that may operate over a string of multiple segments" (Rose & Walker, 2011). In this paper, the segment of interest is the vowel. Vowel Harmony refers to a relationship between vowels such that all vowels within a certain prosodic boundary share a feature. It has been simply and clearly defined by Vago as:

> "a law which governs the co-occurrence of vowels within a span of utterance, nearly always the word." (Vago, 1977, pg. xi).

Vowel harmony constraints are not limited only to the tongue root. Vowel harmony can be manifested through the features of backness, height, roundness, and [ATR] (Polgardi, 2006). Backness harmony refers to the requirement of all vowels in a word to be either all front or all back vowels. Examples of this type of harmony can be found in Tuvan, a Siberian Turkic language. In Tuvan all vowels in a word must be either front vowels or back vowels. In Tuvan, harmony operates such that "the harmony produces alternations in suffix vowels, which take their cue from the backness of the preceding vowel." (Rose &Walker, 2011, p.251). It is unclear whether vowel harmony within Tuvan roots is progressive or regressive.

Turkish also exhibits backness harmony. It appears that in Turkish vowel harmony is progressive, moving from the root word to its suffixes. Backness harmony in Turkish affects suffixes that have the [+ low] feature.

Hungarian serves as an example of language with backness harmony among vowels. Hungarian vowel harmony shows us that backness harmony is not as straight forward as it may be in other languages. In contrast to some of the other languages with backness harmony, Hungarian has mixed vowels that are considered both back and front:

> "According to their vocalic content, root morphemes may be classified as: back vowel roots, containing only the back vowels /u ui o o a a/; front vowel roots, containing only the front vowels /i i e e ii (u 6 o/; and mixed vowel roots, containing the unrounded front vowels /i i e e/ plus back vowels." (Vago, 1976, p. 244)

In some languages, multiple forms of harmony are applied concurrently to the same set of phonological segments. A good example of the different manifestations of vowel harmony is found in a study done on an Italian dialect in which mid vowels in a stressed position cause vowels in the final position to harmonize with the features of backness and roundness (Herrerro and Jimenez, 2009).

Somali Vowel Harmony

While it has been suggested that vowel harmony exists outside of the prosodic word boundary in Somali, what little research has been done has focused mostly on the rules governing vowel harmony within the boundary of the word. Such research suggests that all vowels within a Somali word must have the same [ATR] feature (Saeed, 1999). That is, vowels in Somali words exhibit harmony in the advancement or retraction of the tongue root so that all vowels in a word will be pronounced with the tongue root advanced or with the tongue root either neutral or retracted. Neutral tongue root and retracted tongue root will be treated as synonymous in this study. This is because the feature we are isolating in the present study is the advancement of the tongue root. The evidence has established that it certainly advances from its neutral position, but there is insufficient evidence to suggest that the tongue route in Somali actively retracts in the articulation of a segment.

Examples of Somali [ATR] Vowel Harmony

In Somali, it can be said that there is cross-height vowel harmony. This means that vowels within a word will maintain vowel harmony despite differences in vowel height. As mentioned previously, Somali has the five traditional vowels that English has, however, they are distinguished into two groups differing in the advancement of the tongue root during their articulation. In the examples below, we find words that are [±ATR] though they contain vowels that may vary in height (adopted from Saeed,1999):

(1) [+ATR]

[hilib] Noun = 'meat'

[webi] Noun = 'river'

[sæli:d] Noun = 'oil'

(2) [-ATR]

[Inan] Noun = 'boy'

[damɛ:r] Noun = 'donkey (male)'

[waddɔ] Noun = 'road'

In example 1 above we find that the front vowels [e] and [i] in the word for "river", [webi], share the [+ATR] feature even though they are of different heights. Similarly, the vowels [a] and [ɔ] in the word for "road", [waddɔ], also have different heights, but adhere to the vowel harmony constraint of [-ATR]. The most interesting example is from the vowels [a] and [ɛ:] in the word for donkey, [damɛ:r]. These vowels have multiple differences in articulation including backness, height and length - yet appear in the same word and share the same [-ATR] feature. Unlike some other languages with [ATR] vowel harmony, Somali phonology allows for cross-height harmony.

Chapter III: Methodology

Speakers

There was a total of eight speakers used for this study: four females and four males. All potential participants were given a socio-metric questionnaire to determine their suitability for the project. All selected speakers were from Northern Somalia and their native dialect is the northern/standard dialect. Speakers that lived in Somalia until at least the age of 16 were selected to ensure that they acquired native pronunciation. The minimum level of education for all speakers was completion of secondary education. The participants have the same general level of literacy in Somali.

Speakers will be identified and studied by a coded designator. The traditional way of labeling speakers *M-1* or *F-1* is dispensed with to avoid confusion resulting from female speaker markers and formant markers e.g. "F1" could stand for Formant 1 or Female 1. In this study male speakers are coded as "a number (which ever number of the four speakers they are)" + M. For example, male speaker number 1 would be given the identifier 1-M. Female speakers are coded as "a number (which ever number of the four speakers they are)" + F. For example, female speaker number 1 would be given the identifier 1-F.

Tokens

The tokens analyzed are words selected from prominent Somali dictionaries and a corpus recorded locally for the purposes of this study. To ensure validity in the speech tokens used, the tokens used in this study were words with which the general adult speaker is familiar. The words were non-technical and non-academic. This helped to ensure that the words were recorded as the person would naturally say them. The selected tokens are un-affixed Somali nouns and/or Verbs. Suffixes in Somali have assimilatory influences on preceding vowels and as such, only un-affixed words were included in the present study (Saeed, 1999; Armstrong, 1934). To ensure the minimization of the influence of consonants on expected variations, near minimal pairs were used as much as possible to contrast the different [ATR] sets. The tokens were chosen with care to include minimal pairs having consonants with minimal assimilatory influence on their adjacent vowels.

The corpus used in this study consists of 10 words provided in Table 5 below: a different word for each of the 10 vowels. Each word was repeated three times. This makes for a total of 30 tokens (10 words x 3 utterances) per speaker. The corpus consisted of a total of 240 tokens. For the statistical analyses, the three utterances for each speaker were averaged resulting in 10 vowels for each speaker instead of 30 individual tokens for each speaker.

Table 5

Lexical Items Used in Corpus

No.	1	2	3	4	5	6	7	8	9	10
Lexical Items	/dɪs/	/bijow/	/dɛx/	/deg/	/dar/	/ʔaeb/	/tɔl/	/fog/	/dʊl/	/gun/
Meaning	Build	Water	Middle	Ear	Clothes	Drink	Sew	Far	Ground	Well bottom
Vowels	[i]	[ɪ]	[ɛ]	[e]	[a]	[æ]	[ɔ]	[o]	[ʊ]	[u]

Elicitation

Each speaker was provided with a list of tokens to pronounce three times each. Initially, they were asked to read the entire list of words in one go to ensure that their pronunciation was accurate. This was important because the literacy level of speakers in reading Somali words may vary between speakers. Before they began officially reading each of the 10 words, the speakers were reminded to say the words naturally to prevent over-enunciating and artificially adjusting the voice sounds. To reduce any effects from repetition bias which may result in variations of pitch in strings of words, they were asked to consider each of the three repetitions per word as distinct and not part of a sentence. They were instructed to read a word three times and then take a break of 10 seconds before moving on to the next word. Then they moved on to the next word and repeated the same process until they completed the entire list of 10 words. They were recorded as they produced each of the selected words.

Technology

The speakers were recorded using a Sony ICD-UX523 Digital Voice Recorder. The software used to analyze the data was the current version of PRAAT. The location of the recordings was in the soundproof rooms located in the Education Building at Saint Cloud State University to limit acoustic interference.

Measurements

Using the Praat program, the following 5 measurements were taken: Fundamental Frequency, Formant 1, Formant 2, Formant 3, and Vowel Duration.

Formant Analyses For the formant analyses the following results will be presented:

i. Descriptive summary of the statistical results
ii. Tables of individual and group Formant means for each vowel with its [ATR] counterpart
iii. Bar Graph representing differences in means between phonemes in each [ATR] pair.

The method of analysis for the vowel measurements was to measure the spectral band of the vowel at least 20 ms after the onset of the vowel and within the steady state of the vowel. In order to avoid co-articulatory effects of adjacent segments, measurements were made as closely to the center of the vowel as possible. Figure 1 below displays the waveform and wideband spectrogram for one utterance of the word "?aeb" = "drink" produced by M1 – (Male Speaker 1). It displays a close-up view of the measured pulses in this example. The fundamental frequency and the first three formants were all measured using this shaded area. The same procedure was followed for all vowels in this study.

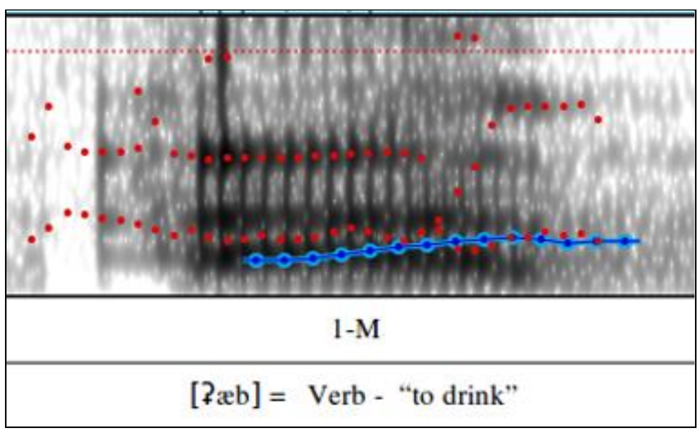

Figure 1 - Spectrogram Sample from Speaker 1-M

Research Questions

1. Do [+ATR] vowels have significantly higher relative pitch (F0) than [-ATR] vowels?
2. Do [-ATR] vowels have significantly lower F1 values than [-ATR] vowels?
3. Do [+ATR] vowels have significantly higher F2 values than [-ATR] vowels?
4. Do [+ATR] vowels have significantly higher F3 values than [-ATR] vowels?
5. Are [+ATR] vowels significantly longer in duration than [-ATR] vowels?

Chapter IV: Results

In this section, the results of the statistical test designed to assess the significance of differences in [ATR] vowel sets are presented. The results include the values for each correlate of the tokens produced by the 8 speakers. A summary of the independent samples t-test results and the results from the observation of differences in values between phonemes in [ATR] pairs are presented for each correlate. The means for male and female speakers are also presented with graphs illustrating differences in values and tables summarizing the mean differences.

F0– Fundamental Frequency (Pitch) – Results and Summary

Fundamental frequencies were important to this study because they are the primary source of distinction in the perception of pitch (Baart, 2010). In general, a lower fundamental frequency will correspond with a lower pitch and vice versa.

Using an α level of .05, an independent-samples t-test was conducted to evaluate whether F0 frequencies differed significantly between phonemes [i] vs. [ɪ], [e] vs. [ɛ], [æ] vs. [ɑ], [o] vs. [ɔ] and [u] vs. [ʊ] as a function of whether the phonemes were [±ATR]. The F0 values for both ± [ATR] phonemes followed a normal distribution and met the conditions for conducting a t-test. The results of the t-tests across all phoneme pairs indicate that, as a function of [±ATR], the differences between F0 values are not significant. As summarized in Table 6 below, the p-scores are all well above the .05 α level. None of the phoneme pairs demonstrate significance for the F0 Correlate.

Table 6

Results of Independent Samples t-tests for F0 (Fundamental Frequency)

Phoneme Pair	Correlate	Mean Difference	t	df	p
[i] vs [ɪ]	F0	26	-0.98	14	0.34
[e] vs [ɛ]	F0	-1.45	-0.05	14	0.954
[æ] vs [ɑ]	F0	-9.62	-0.41	14	0.68
[o] vs [ɔ]	F0	14.4	0.61	14	0.54
[u] vs [ʊ]	F0	13.33	0.48	14	0.633

The individual speaker means below in Tables 7 and 8 indicate there is inconsistency between the speaker values and more importantly in the direction of the variation between the phonemes in each [ATR] pair.

Table 7

F0 Male Speakers - Means and Standard Deviations

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	130	150	156	156	133	149	156	149	156	151
Speaker 2M	100	123	120	121	106	110	123	123	142	138
Speaker 3M	122	138	140	121	139	127	159	151	164	153
Speaker 4 M	173	176	204	185	176	189	212	173	207	212
Mean	**131**	**147**	**155**	**146**	**139**	**144**	**163**	**149**	**167**	**164**
Standard Dev.	**26**	**19**	**31**	**27**	**25**	**30**	**32**	**18**	**24**	**29**

Table 8

F0 Female Speakers - Means and Standard Deviations

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	229	265	240	252	210	227	239	216	317	253
Speaker 2F	203	271	235	257	230	241	255	235	269	248
Speaker 3F	199	198	219	219	207	205	234	219	240	245
Speaker 4 F	202	247	202	215	184	214	239	235	231	220
Mean	**208**	**245**	**224**	**236**	**208**	**222**	**242**	**226**	**264**	**242**
Standard Dev.	**14**	**33**	**17**	**22**	**19**	**16**	**9**	**10**	**39**	**15**

Figures 2 and 3 below, illustrate that the F0 values were not consistently higher for [+ATR] vowels. In Tables 9 and 10 below, F0 means for the [+ATR] vowels were sometimes slightly higher than [-ATR] vowels and sometimes slightly lower for male and female speakers. The [+ATR] vowels (N = 8) were not significantly higher than their [-ATR] vowel (N = 8) counterparts. A noticeable, but not statistically significant, difference in means for fundamental frequency is exhibited only in the /i/ vs / ɪ / [ATR] pair as in tables 9 and 10 below.

The graph in Figure 2 below illustrates the differences in means between phonemes in each set of [ATR] pairs for male speakers. At 16 Hz, the greatest difference in means is observed in [ATR] phoneme pair [i] and [ɪ]. The t-test, however, did not demonstrate a significant effect. The differences in means was not significant nor consistent in the direction [+/-] of the difference across ATR pairs.

Figure 2 - Male F0 (Hz) Average Values

The graph in Figure 3 below illustrates the differences in fundamental frequency (F0) between each set of [ATR] pairs for female speakers. At 37 Hz, the greatest difference in means is observed between [ATR] phoneme pairs [i] and [ɪ]. The t-test did not demonstrate a significant effect. The differences in means was not significant nor consistent in the direction [+/-] of the difference across ATR pairs.

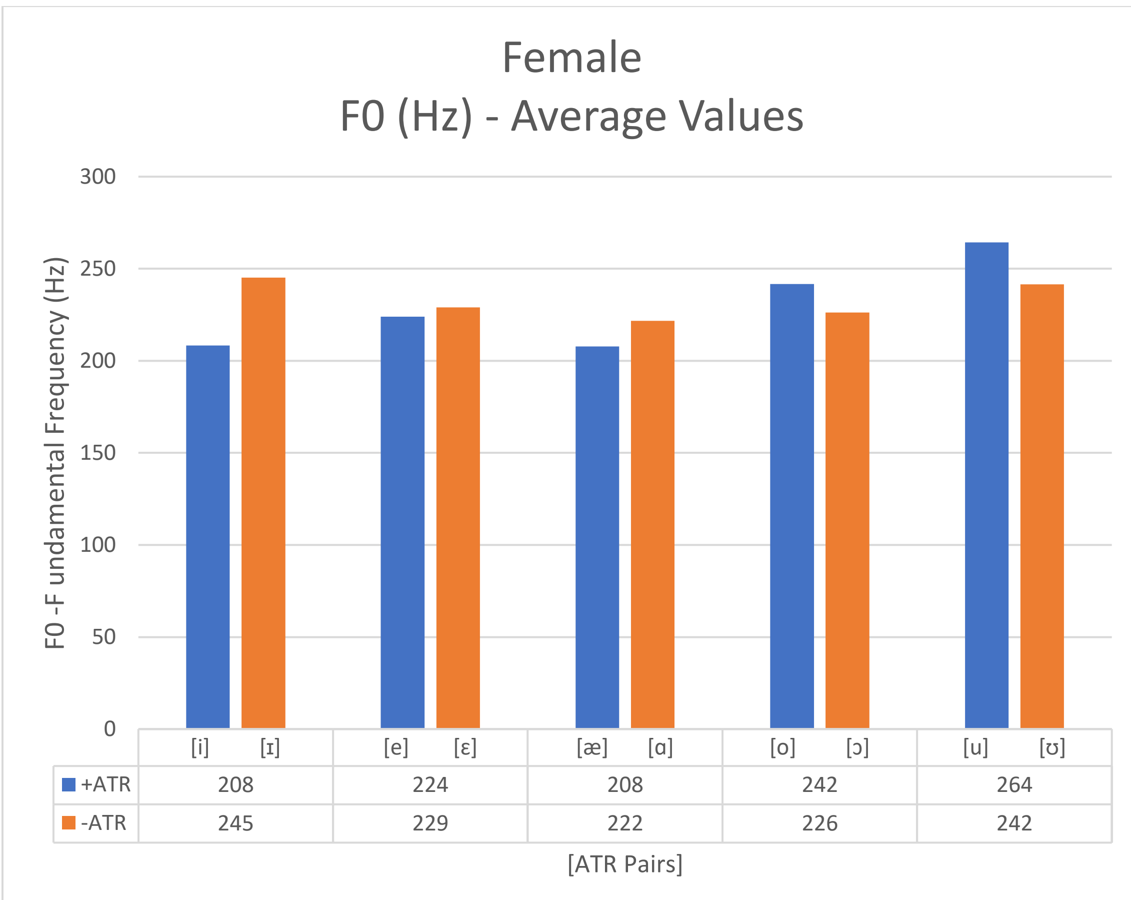

Figure 3 - Female F0 (Hz) Average Values

Differences in F0 Means between Harmonic Pairs

[i] vs. [ɪ] for F0 Frequencies

For male speakers, the mean F0 value of the [+ATR] phoneme **[i]** (M=131 Hz) was lower than the value of the [-ATR] phoneme **[ɪ]** (M = 147 Hz) by 16 Hz. For female speakers, the mean F0 value of the [+ATR] phoneme **[i]** (M= 208 Hz) was lower than the mean value of the [-ATR] phoneme **[ɪ]** (M = 245 Hz) by 37 Hz.

[e] vs. [ɛ] for F0 Frequencies

For male speakers, the mean F0 value of the [+ATR] phoneme **[e]** (M = 155 Hz) was higher than the mean value of the [-ATR] phoneme **[ɛ]** (M = 146 Hz) by 9 Hz. For female speakers, the mean F0 value of the [+ATR] phoneme **[e] (**M=224 Hz) was lower than the mean value of the [-ATR] phoneme **[ɛ]** (M =236 Hz) by 12 Hz.

[æ] vs. [ɑ] for F0 Frequencies

For male speakers, the mean F0 value of the [+ATR] phoneme **[æ]** (M= 139 Hz) was lower than the mean value of [-ATR] phoneme **[ɑ]** (M = 144 Hz) by 5 Hz. For female speakers, the mean F0 value of the [+ATR] phoneme **[æ] (**M= 208 Hz) was lower than the mean value of the [-ATR] phoneme **[ɑ]** (M = 222 Hz) by 14 Hz.

[o] vs. [ɔ] for F0 Frequencies

For male speakers, the mean F0 value for the [+ATR] phoneme **[o]** (M=163 Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 149 Hz) by 14 Hz. For female speakers, the mean F0 value of the [+ATR] phoneme **[o] (**M=242 Hz) was higher than the [-ATR] phoneme **[ɔ]** (M = 226 Hz) by 16 Hz.

[u] vs. [ʊ] for F0 Frequencies

For male speakers, the mean F3 value of the [+ATR] phoneme **[u]** (M=167Hz) was higher than the mean value of the [-ATR] phoneme **[ʊ]** (M = 164 Hz) by 3 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[u] (**M= 264 Hz) was higher than the mean value of the [-ATR] phoneme **[ʊ]** (M = 242Hz) by 22 Hz.

Table 9

Differences in Means - Male - F0 (Relative Pitch/ Fundamental Frequency)

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F0 (Hz)	131	147	155	146	139	144	163	149	167	164
Mean Difference	**16 Hz**		**-9 Hz**		**5 Hz**		**-14 Hz**		**-3 Hz**	

Table 10

Differences in Means - Female - F0 (Relative Pitch/ Fundamental Frequency)

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F0 (Hz)	208	245	224	236	208	222	242	226	264	242
Mean Difference (Hz)	**37 Hz**		**12 Hz**		**14 Hz**		**-16 Hz**		**-22 Hz**	

F1 – First Formant (Vowel Height) – Results and Summary

The first formant determines vowel height across the pairs. Vowel height is negatively correlated with F1 frequency values, so the higher vowels have a lower F1 value. In this section glottal pulses were selected for measurement from the steady state region of each vowel as is the practice in contemporary measurements of formants (Anderson, 2007; Starwalt, 2008). To eliminate co-articulatory effects of adjacent vowels, measurements began between 20 and 30 milliseconds from the onset of the vowel. Here the focus was on minimizing the consequences of the overlap in formant values.

Using an α level of .05, an independent-samples *t*-test was conducted to evaluate whether F1 frequencies differed between phoneme pairs [i] vs. [ɪ], [e] vs. [ɛ], [æ] vs. [ɑ], [o] vs. [ɔ] and [u] vs. [ʊ] as a function of whether the phonemes were [±ATR]. The F1 values for both [±ATR] phonemes followed a normal distribution and met the conditions for conducting a t-test. The tests indicate significance ($p < 0.05$) in four out of the five [ATR] phoneme pairs. The t-test for the phoneme pair [i] vs [ɪ] was associated with a significant effect, $t(14) = -4$, $p = 0.001$. The phoneme pair [e] vs [ɛ] was associated with a significant effect, $t(14) = -3.75$, $p = 0.002$. The phoneme pair [o] vs [ɔ] was associated with a significant effect, $t(14) = -5.09$, $p = 0$. The phoneme pair [u] vs [ʊ] was associated with a significant effect, $t(14) = -3.85$, $p = 0.002$. As summarized in Table 11, F1 is statistically reliable in discriminating between [+ATR] and [-ATR] vowels for these four phoneme pairs.

Table 11

Results of Independent Samples t-test for F1 (Fundamental Frequency)

Phoneme Pair	Correlate	Mean Difference	t	df	p
[i] vs [ɪ]	F1	-121	-4	14	0.001√
[e] vs [ɛ]	F1	-123.54	-3.75	14	0.002 √
[æ] vs [ɑ]	F1	105.66	1.68	14	0.115
[o] vs [ɔ]	F1	-118.25	-5.09	14	0.00 √
[u] vs [ʊ]	F1	-73.83	-3.85	14	0.002 √

The individual speaker means below in Tables 12 and 13 indicate there is consistency between the speaker values for the four [ATR] pairs that demonstrated significance. In addition, there was consistency in the direction of the variation between the phonemes in each [ATR] pair.

Table 12

F1 Male Speakers - Means and Standard Deviations

F1(Hz)	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	268	397	483	523	750	609	479	556	377	430
Speaker 2M	276	413	494	617	828	733	514	635	378	486
Speaker 3M	410	434	459	575	785	631	484	601	353	465
Speaker 4 M	268	414	463	615	679	639	448	567	415	435
Mean	**306**	**415**	**475**	**583**	**761**	**653**	**481**	**590**	**381**	**454**
Standard Dev.	**60**	**13**	**14**	**38**	**55**	**47**	**23**	**31**	**22**	**23**

Table 13

F1- Female Speakers - Means and Standard Deviations

F1 (Hz)	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	419	533	557	737	834	850	564	683	376	511
Speaker 2F	334	503	528	757	692	487	527	660	452	492
Speaker 3F	275	401	541	654	914	902	540	658	385	488
Speaker 4 F	377	504	608	643	1009	792	552	693	485	505
Mean	**351**	**485**	**559**	**698**	**862**	**758**	**546**	**674**	**425**	**499**
Standard Dev.	**53**	**50**	**30**	**50**	**116**	**161**	**14**	**15**	**46**	**9**

Figures 4 and 5 below illustrate that the F1 values are consistently lower for [+ATR] vowels. In Tables 14 and 15 below, the mean F1 values for the [+ATR] vowels were consistently lower for both male and female speakers. The [+ATR] vowels (N = 8) have a statistically significant lower frequency than their [-ATR] (N = 8) vowel counterparts for four of the five [ATR] vowel pairs. The only vowel pair that has a low difference in means is [ae] vs [ɑ]for Male speakers.

The graph in Figure 4 below illustrates the differences in the first formant (F1) between phonemes in each set of [ATR] pairs for male speakers. In each of the measurements above, the [+ATR] phonemes are lower in F1 frequencies than their [-ATR] counterparts. At 109 Hz, the greatest difference in means is observed between the [ATR] phoneme pairs [o] vs. [ɔ] and and [i] vs [ɪ]. However, [e] vs [ɛ] and [æ] vs. [ɑ] pairs also exhibit differences in means within that range with a mean difference of 108 Hz each.

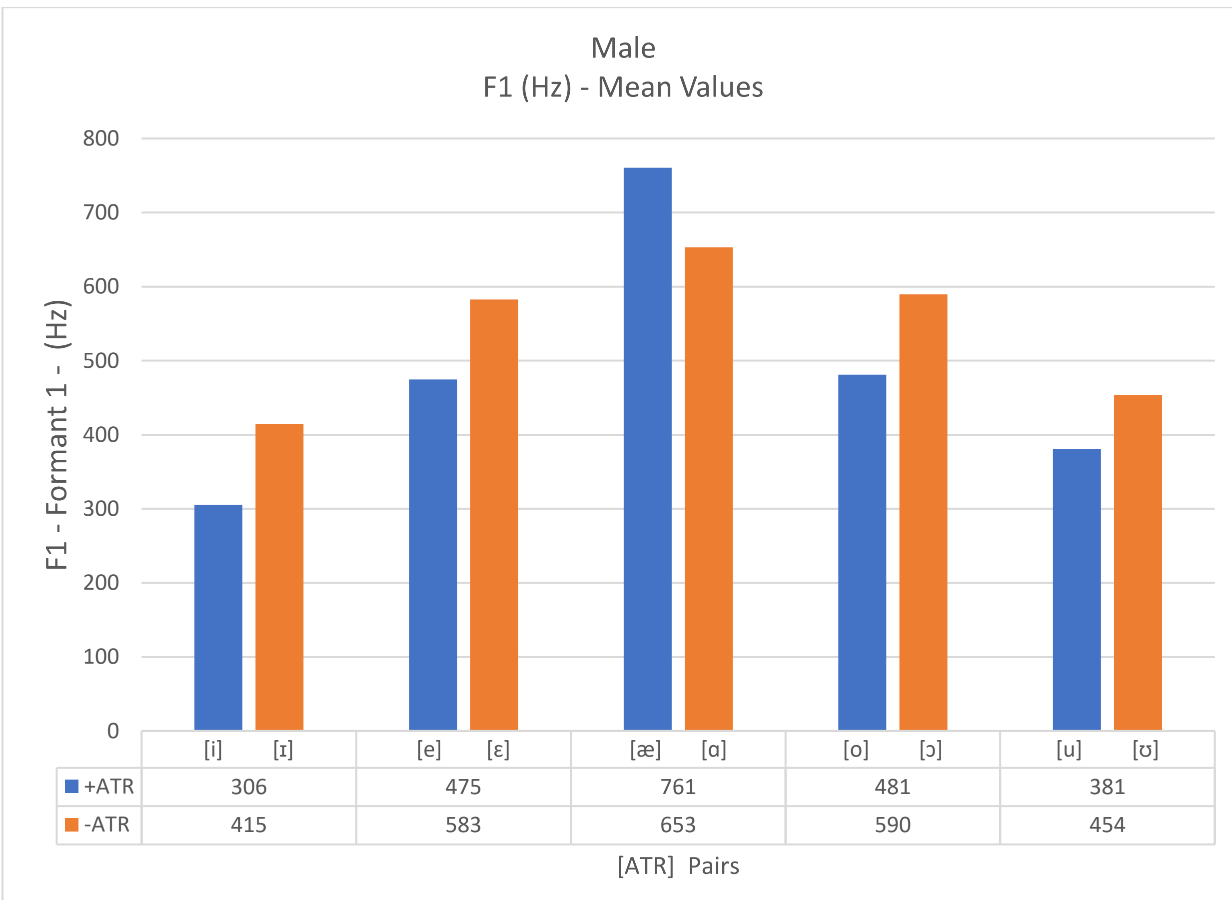

Figure 4 - Male F1 (Hz) Mean Values

The graph in Figure 5 below illustrates the differences in the first formant (F1) between phonemes in each set of [ATR] pairs for female speakers. In four of the measurements above, the [+ATR] phonemes are lower in F1 frequencies than their [-ATR] counterparts. At 139 Hz, the greatest difference in means is observed between the [ATR] phoneme pair [e] vs [ɛ].

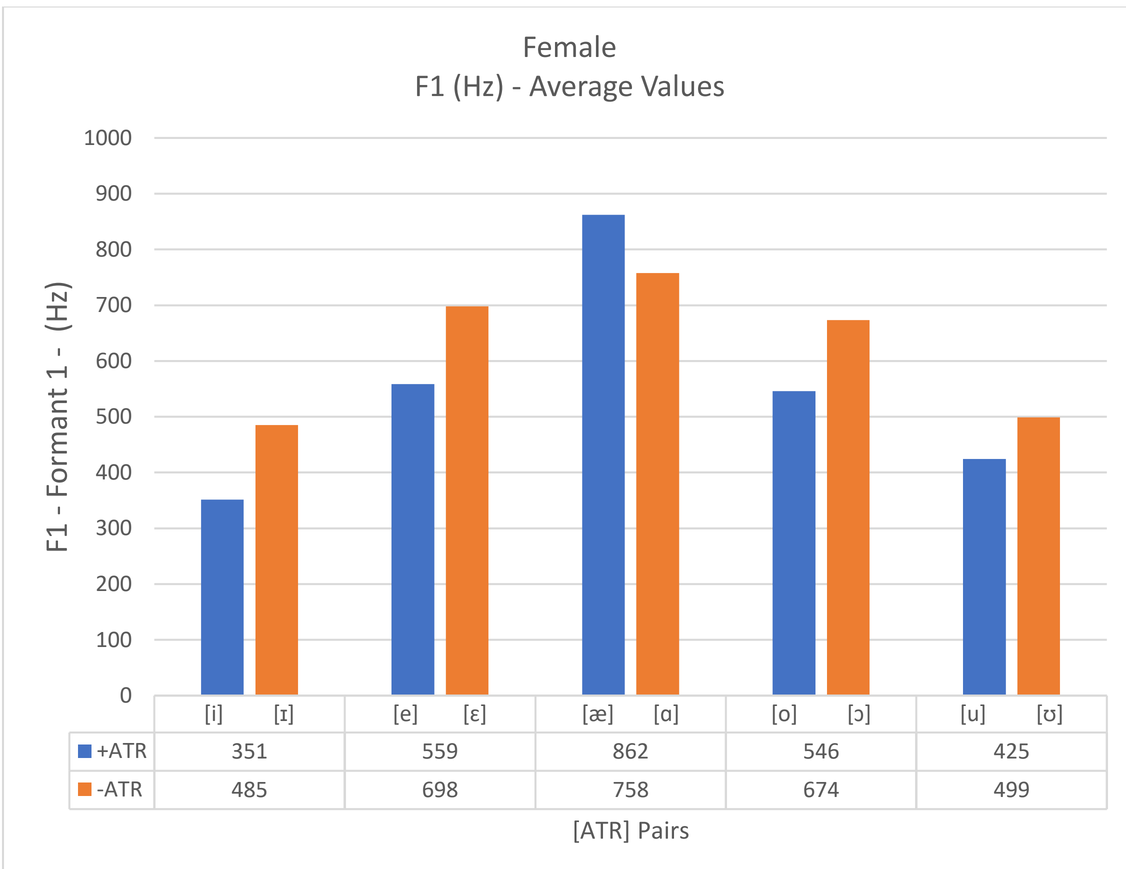

Figure 5 - Female F1 (Hz) Average Values

Differences in F1 Means between Harmonic Pairs

[i] vs. [ɪ] for F1 Frequencies

For male speakers, the mean F1 value of the [+ATR] phoneme **[i]** (M=306 Hz) was lower than the value of the [-ATR] phoneme **[ɪ]** (M = 415 Hz) by 109 Hz. For female speakers, the mean F1 valueof the [+ATR] phoneme **[i]** (M=351 Hz) was lower than the mean value of the [-ATR] phoneme **[ɪ]** (M = 485 Hz) by 134 Hz.

[e] vs. [ɛ] for F1 Frequencies

For male speakers, the mean F1 value of the [+ATR] phoneme **[e]** (M = 475 Hz) was lower than the mean value of the [-ATR] phoneme **[ɛ]** (M = 583 Hz) by 108 Hz. For female speakers, the mean F1 valueof the [+ATR] phoneme **[e] (**M=559 Hz) was lower than the mean value of the [-ATR] phoneme **[ɛ]**(M = 698 Hz) by 139 Hz.

[æ] vs. [ɑ] for F1 Frequencies

For male speakers, the mean F1 value of the [+ATR] phoneme **[æ]** (M=761 Hz) was higher than the mean value of [-ATR] phoneme **[ɑ]** (M = 653 Hz) by 108 Hz. For female speakers, the mean F1 value of the [+ATR] phoneme **[æ] (**M=862 Hz) was higher than the mean value of the [-ATR] phoneme **[ɑ]** (M = 758 Hz) by 104 Hz.

[o] vs. [ɔ] for F1 Frequencies

For male speakers, the mean F1 value for the [+ATR] phoneme **[o]** (M = 481Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 590 Hz) by 109 Hz. For female speakers, the mean F1 value of the [+ATR] phoneme **[o] (**M=546 Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 674 Hz) by 128 Hz.

[u] vs. [ʊ] for F1 Frequencies

For male speakers, the mean F1 value of the [+ATR] phoneme **[u]** (M =381 Hz) was lower than the mean value of the [-ATR] phoneme **[ʊ]**(M = 454 Hz) by 73 Hz. For female speakers, the mean F1 value of the [+ATR] phoneme **[u] (**M = 425 Hz) was lower than the mean value of the [-ATR] phoneme **[ʊ]** (M = 499 Hz) by 74 Hz.

Table 14

Male F1 (Hz) - Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F1 (Hz)	306	415	475	583	761	653	481	590	381	454
Male - Average Difference (Hz)	**- 109 Hz**		**- 108 Hz**		**108 Hz**		**- 109 Hz**		**- 73 Hz**	

Table 15

Female F1 (Hz) -Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F1 (Hz)	351	485	559	698	862	758	546	674	425	499
Female - avg Difference (Hz)	**- 134 Hz**		**- 139 Hz**		**104 Hz**		**- 128 Hz**		**- 74 Hz**	

F2 – Second Formant (Vowel Backness) – Results and Summary

The second formant values correspond to the backness of vowels across the pairs. The more forward the vowel is in its articulation the higher the F2 value. The same process was followed for measuring the second formant as was followed for measuring the first formant.

Using an α level of .05, an independent-samples t-test was conducted to evaluate whether F2 frequencies differed in phoneme pairs [i] vs. [ɪ], [e] vs. [ɛ], [æ] vs. [ɑ], [o] vs. [ɔ] and [u] vs. [ʊ] as a function of whether the phonemes were [±ATR]. The F2 values for both [±ATR] phonemes followed a normal distribution and met the conditions for conducting a t-test. The test indicates significance ($p < 0.05$) in two out of the five phoneme pairs. The t-test for the phoneme pair [i] vs [ɪ] was associated with a significant effect, $t(14) = 3.5$, $p = 0.003$. The t-test for the phoneme pair [æ] vs [ɑ] was associated with a significant effect, $t(14) = 2.69$, $p = 0.017$. As summarized in table 16 below, only phoneme pairs [i] vs [ɪ] and [æ] vs [ɑ] demonstrate significance for the F2 correlate.

Table 16

Results of Independent Samples t-test for F2 (Fundamental Frequency)

Phoneme Pair	**Correlate**	**Mean Difference**	**t**	**df**	**p**
[i] vs [ɪ]	F2	316	3.5	14	0.003√
[e] vs [ɛ]	F2	101.58	1.08	14	0.294
[æ] vs [ɑ]	F2	291.208	2.69	14	0.017√
[o] vs [ɔ]	F2	-44.79	-0.94	14	0.36
[u] vs [ʊ]	F2	88.29	1.01	14	0.32

The individual speaker means below in Tables 17 and 18 indicate there is consistency between the speaker values only for the vowel pairs that demonstrated statistical significance- [i] vs [ɪ] and [æ] vs [ɑ]. The other phoneme pairs exhibit a lot of inconsistency in the direction of the variation between the phonemes in those [ATR] pairs for both male and female speakers.

Table 17

F2 - Male Speakers - Means and Standard Deviations

F2	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	2101	1791	1646	1666	1407	1196	1007	1008	995	913
Speaker 2M	2177	1965	2018	1788	1508	1359	1128	978	1058	869
Speaker 3M	2241	1838	1983	1635	1768	1442	1126	1118	1169	1113
Speaker 4 M	2171	2106	2088	1917	1365	1287	1021	1048	1074	951
Mean	**2173**	**1925**	**1934**	**1752**	**1512**	**1321**	**1071**	**1038**	**1074**	**962**
Standard Dev.	**50**	**122**	**170**	**111**	**157**	**91**	**57**	**52**	**62**	**92**

Table 18

F2 - Female Speakers - Means and Standard Deviations

F2	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	2552	2189	2196	2195	1757	1627	1078	1211	1237	1206
Speaker 2F	2655	2227	2154	2078	1985	1059	1160	1316	1143	1219
Speaker 3F	2364	2073	2005	2091	1845	1493	954	1077	905	964
Speaker 4 F	2415	1958	2012	1918	1813	1657	1104	1182	1563	1201
Mean	**2497**	**2112**	**2092**	**2071**	**1850**	**1459**	**1074**	**1197**	**1212**	**1148**
Standard Dev.	**114**	**105**	**85**	**99**	**84**	**239**	**75**	**85**	**236**	**106**

Figures 6 and 7 below illustrate that the mean F2 values for the [+ATR] vowels were consistently lower for both male and female speakers. In Tables 19 and 20, the mean F2 values were consistently, but not significantly, greater for [+ATR] vowels [æ] vs. [ɑ] and [i] vs. [ɪ].

The graph below in Figure 6 illustrates the differences in the second formant (F2) frequencies between phonemes in each [ATR] pair for male speakers. In each of the measurements above, the [+ATR] phonemes are higher in F2 frequencies than their [-ATR] counterparts. At 248 Hz, the greatest difference in means is observed between the [ATR] phoneme pair [i] vs. [ɪ].

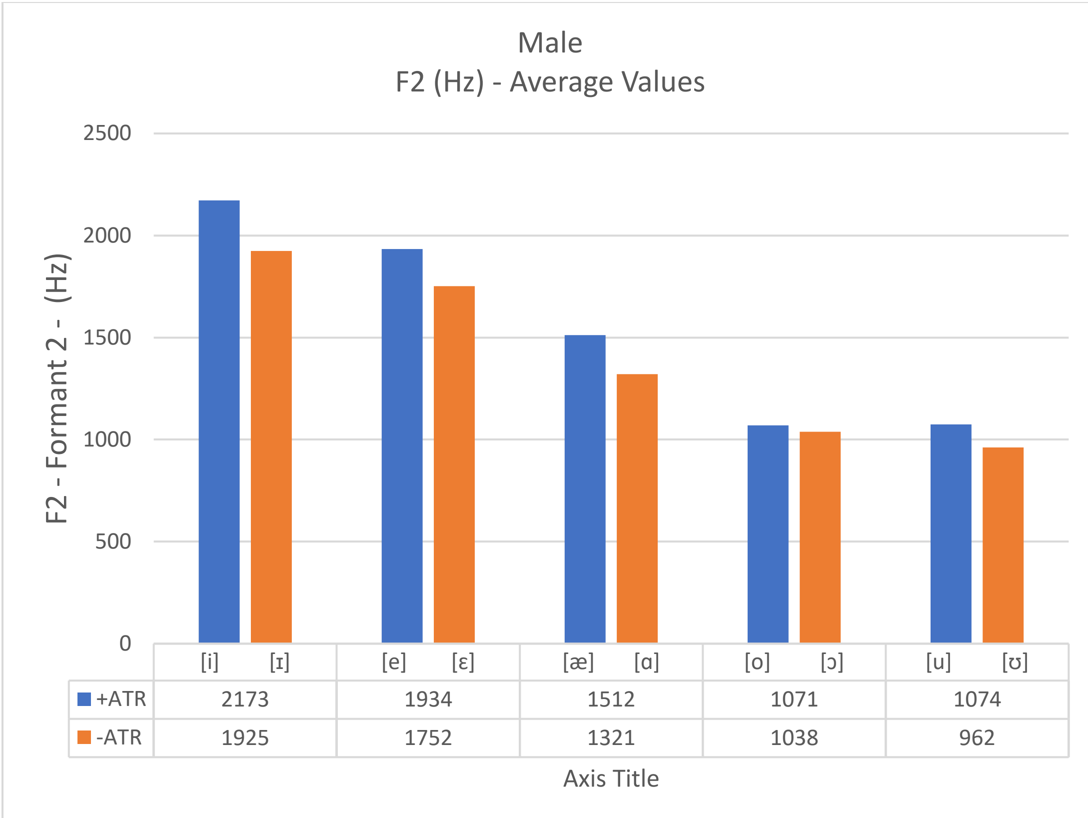

Figure 6 - Male F2 (Hz) - Mean Values

The graph in Figure 7 below illustrates the differences in the second formant (F2) frequencies between phonemes in each set of [ATR] pairs for female speakers. In four of the measurements above, the [+ATR] phonemes are higher in F2 frequencies than their [-ATR] counterparts, the exception being [o] vs [ɔ]. At 391 Hz, the greatest difference in means is observed between the [ATR] phoneme pair [æ] vs [ɑ]. At 385 Hz, there is also a large difference between [i] vs. [ɪ].

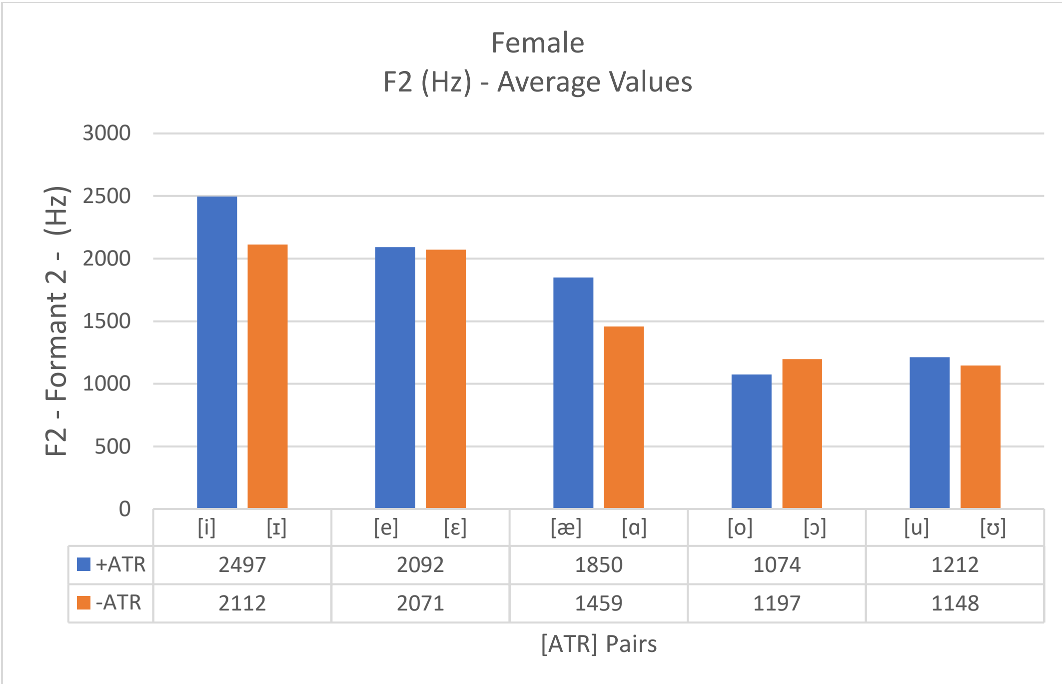

Figure 7 – Female F2 (Hz) – Average Values

Differences in F2 Means between Harmonic Pairs

[i] vs. [ɪ] for F2Frequencies

For male speakers, the mean F2 value of the [+ATR] phoneme **[i]** (M=2173 Hz) was higher than the value of the [-ATR] phoneme **[ɪ]** (M = 1925 Hz) by 248 Hz. For female speakers, the mean F2 value of the [+ATR] phoneme **[i]** (M=2497 Hz) was higher than the mean value of the [-ATR] phoneme **[ɪ]** (M = 2112 Hz) by 385 Hz.

[e] vs. [ɛ]for F2Frequencies

For male speakers, the mean F2 value of the [+ATR] phoneme **[e]** (M = 1934 Hz) was higher than the mean value of the [-ATR] phoneme **[ɛ]** (M = 1752 Hz) by 186 Hz. For female speakers, the mean F2 value of the [+ATR] phoneme **[e] (**M=2092 Hz) was higher than the mean value of the [-ATR] phoneme **[ɛ]** (M =2071 Hz) by 21 Hz.

[æ] vs. [ɑ] for F2 Frequencies

For male speakers, the mean F2 value of the [+ATR] phoneme **[æ]** (M=1512 Hz) was higher than the mean value of [-ATR] phoneme **[ɑ]** (M = 1321 Hz) by 191 Hz. For female speakers, the mean F2 value of the [+ATR] phoneme **[æ] (**M= 1850 Hz) was higher than the mean value of the [-ATR] phoneme **[ɑ]** (M = 1459 Hz) by 391 Hz.

[o] vs. [ɔ] for F2Frequencies

For male speakers, the mean F2 value for the [+ATR] phoneme **[o]** (M=1071 Hz) was higher than the [-ATR] phoneme **[ɔ]** (M = 1038 Hz) by 33 Hz. For female speakers, the mean F2 value of the [+ATR] phoneme **[o] (**M=1074 Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 1197 Hz) by 123 Hz.

[u] vs. [ʊ] for F2 Frequencies

For male speakers, the mean F2 value of the [+ATR] phoneme **[u]** (M=1074 Hz)was higher than the mean value of the [-ATR] phoneme **[ʊ]** (M = 962 Hz) by 112 Hz. For female speakers, the mean F2 value of the [+ATR] phoneme **[u] (**M=1212 Hz) was higher than the mean value of the [-ATR] phoneme **[ʊ]** (M = 1148 Hz) by 64 Hz.

Table 19

Male F2 (Hz) – Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F2 (Hz)	2173	1925	1934	1752	1512	1321	1071	1038	1074	962
Male Average Difference (Hz)	**248 Hz**		**186 Hz**		**191 Hz**		**33 Hz**		**112 Hz**	

Table 20

Female F2 (Hz) – Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F2 (Hz)	2497	2112	2092	2071	1850	1459	1074	1197	1212	1148
Female Average Difference (Hz)	**385 Hz**		**21 Hz**		**391 Hz**		**-123 Hz**		**64 Hz**	

F3 – Formant 3 (Vocal Tract Rounding) – Results and Summary

F3 has been tested for its relationship with [ATR] in several African languages. The assumption is that F3 is a potential correlate of [ATR] due to its relationship to lip rounding and the curving of the tongue in the pronunciation of [+ATR] vowels. As mentioned by Kang and Ko, early studies on F3 suggested that it was perhaps related to the pharyngealization in the articulation of certain vowels (2012).

Using an α level of .05, an independent-samples t-test was conducted to evaluate whether F3 frequencies differed in phoneme pairs [i] vs. [ɪ], [e] vs. [ɛ], [æ] vs. [ɑ], [o] vs. [ɔ] and [u] vs. [ʊ] as a function of whether the phonemes were [±ATR]. The F3 values for both [±ATR] phonemes followed a normal distribution and met the conditions for conducting a t-test. The test indicates significance ($p < 0.05$) in one out of the five phoneme pairs. The t-test for the phoneme pair [i] vs [ɪ] was associated with a significant effect, $t(14) = 2.2$, $p = 0.045$. As summarized in Table 21 below, this is the only phoneme that demonstrated significance for the F3 correlate.

Table 21

Results of Independent Samples t-test for F3

Phoneme Pair	Correlate	Mean Difference	t	df	p
[i] vs [ɪ]	F3	278	2.2	14	0.045√
[e] vs [ɛ]	F3	-99.62	-0.7	14	0.494
[æ] vs [ɑ]	F3	-20.83	-0.12	**14**	0.902
[o] vs [ɔ]	F3	-160.54	-1.04	**14**	0.31
[u] vs [ʊ]	F3	88.7	-0.71	**14**	0.486

The individual speaker means below in Tables 22 and 23 indicate there is consistency between the speaker values only for the vowel pair that demonstrated statistical significance [i] vs [ɪ]. The other phoneme pairs exhibit a lot of inconsistency in the direction of the variation between the phonemes in those [ATR] pair for both male and female speakers.

Table 22

F3 Male Speakers - Means and Standard Deviations

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	2672	2415	2234	2387	2522	2555	2253	2685	2367	2442
Speaker 2M	3008	2455	2371	2309	2214	2223	2070	2368	2142	2443
Speaker 3M	3056	2715	2493	2635	2590	2280	2382	2636	2304	2402
Speaker 4 M	2914	2661	2638	2500	2390	2549	2366	2598	2405	2495
Mean	**2913**	**2562**	**2434**	**2458**	**2429**	**2402**	**2268**	**2572**	**2305**	**2446**
Standard Dev.	**148**	**129**	**149**	**123**	**143**	**152**	**125**	**122**	**101**	**33**

Table 23

F3 - Female Speakers - Means and Standard Deviations

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	3113	3170	2927	3224	3212	3264	2931	3090	2988	2788
Speaker 2F	3543	2787	2563	3039	2336	2500	2660	2374	2683	2764
Speaker 3F	2753	2729	2646	2607	2347	2372	2618	2592	2754	2811
Speaker 4 F	3011	2911	2904	2872	2826	2860	2952	3175	2715	2921
Mean	3105	2899	2760	2936	2680	2749	2790	2808	2785	2821
Standard Dev.	285	170	158	227	365	347	152	335	120	60

Figures8 and 9 below, illustrate that the F3values were not consistently higher for [+ATR] vowels. In Tables 24 and 25 below, F3 means for the [+ATR] vowels were sometimes slightly higher than [-ATR] vowels and sometimes slightly lower for both male and female speakers. The [+ATR] vowels (N = 8) were not significantly higher than their [-ATR] vowel (N = 8) counterparts. A statistically significant difference in means for F3 is exhibited only in the [i] vs. [ɪ] [ATR] pair.

The graph in Figure 8 below illustrates the differences in the third formant (F3) frequencies between phonemes in each [ATR] pair for male speakers. In the measurements above, the [+ATR] phonemes are higher in F3 frequencies than their [-ATR] counterparts for vowel pairs [i] vs [ɪ] and [æ] vs. [ɑ]. The effect is reversed for the other three phoneme pairs. At 351 Hz, the greatest difference in means is observed between the [ATR] phoneme pair [i] vs [ɪ].

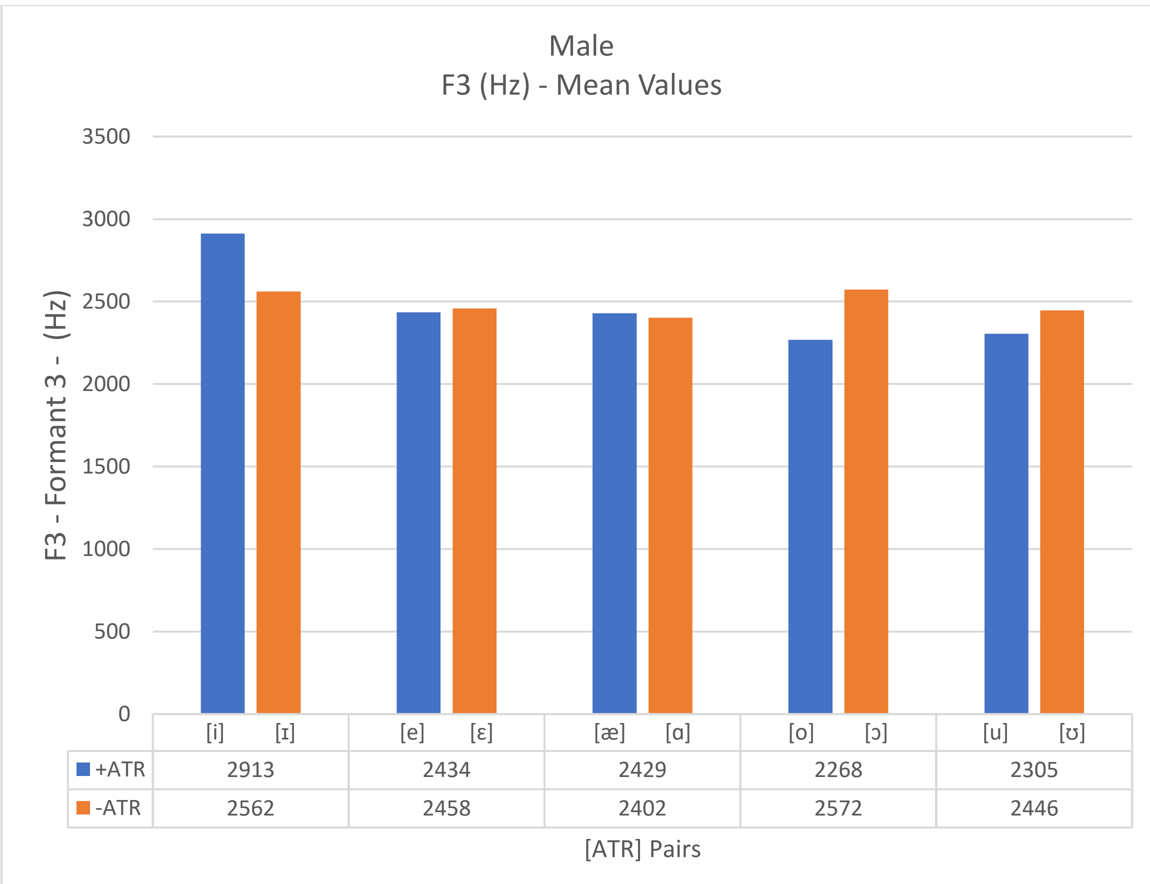

Figure 8 - Male F3 (Hz) - Mean Values

The graph in Figure 9 below illustrates the differences in the third formant (F3) frequencies between phonemes in each [ATR] pair for female speakers. In the measurements above, the [+ATR] phonemes are higher in F3 frequencies than their [-ATR] counterparts for vowel pairs [i] vs [ɪ] and [o] vs [ɔ]. The effect is reversed for the other three phoneme pairs. At 154 Hz, the greatest difference in means is observed between the [ATR] phoneme pair [i] vs [ɪ].

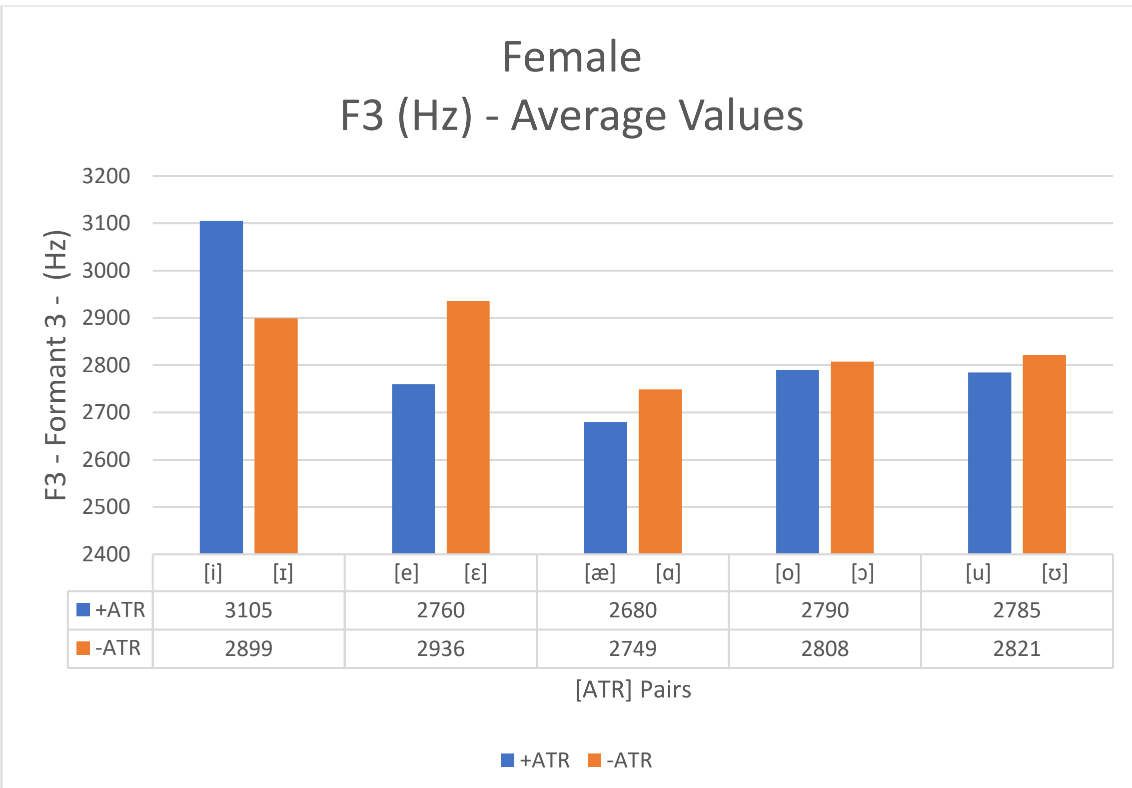

Figure 9 - Female F3 (Hz) - Mean Values

Differences in F3 Means between Harmonic Pairs

[i] vs. [ɪ] for F3 Frequencies

For male speakers, the mean F3 value of the [+ATR] phoneme **[i]** (M = 2913 Hz) was higher than the value of the [-ATR] phoneme **[ɪ]** (M = 2562 Hz) by 351 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[i]** (M =3105 Hz) was higher than the mean value of the [-ATR] phoneme **[ɪ]** (M = 2899 Hz) by 206 Hz.

[e] vs. [ɛ]for F3 Frequencies

For male speakers, the mean F3 value of the [+ATR] phoneme **[e]** (M = 2434 Hz) was lower than the mean value of the [-ATR] phoneme **[ɛ]** (M = 2458 Hz) by 24 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[e]** (M=2760 Hz) was lower than the mean value of the [-ATR] phoneme **[ɛ]** (M =2936 Hz) by 176 Hz.

[æ] vs. [ɑ] for F3 Frequencies

For male speakers, the mean F3 value of the [+ATR] phoneme **[æ]** (M=2429 Hz) was higher than the mean value of [-ATR] phoneme **[ɑ]** (M = 2402 Hz) by 27 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[æ] (**M= 2680 Hz) was lower than the mean value of the [-ATR] phoneme **[ɑ]** (M = 2749 Hz) by69 Hz.

[o] vs. [ɔ]for F3 Frequencies

For male speakers, the mean F3 value for the [+ATR] phoneme **[o]** (M= 2268 Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 2572 Hz) by 304 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[o] (**M= 2790 Hz) was lower than the [-ATR] phoneme **[ɔ]** (M = 2808 Hz) by 18 Hz.

[u] vs. [ʊ] for F3 Frequencies

For male speakers, the mean F3 value of the [+ATR] phoneme **[u]** (M=2305 Hz) was lower than the mean value of the [-ATR] phoneme **[ʊ]** (M = 2446 Hz) by -141 Hz. For female speakers, the mean F3 value of the [+ATR] phoneme **[u] (**M=2785 Hz) was lower than the mean value of the [-ATR] phoneme **[ʊ]** (M = 2821 Hz) by 36 Hz.

Table 24

F3 (Hz) – Male – Summary of Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F3 (Hz)	2913	2562	2434	2458	2429	2402	2268	2572	2305	2446
Male Average Difference (Hz)	**351**		**-24**		**27**		**-304**		**-141**	

Table 25

F3 (Hz) – Female – Summary of Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F3 (Hz)	3105	2899	2760	2936	2680	2749	2790	2808	2785	2821
Female Average Difference (Hz)	**206**		**-176**		**-69**		**-18**		**-36**	

Duration – Results and Summary

The role of [ATR] in duration has been studied for many languages resulting in varying results. The language of Akan was studied by Hess (1992) where the duration of vowels was tested for between [+ATR] vowels and [– ATR] vowels with mixed results. Guion et al (2004) found significant durational variation between the [ATR] sets for certain back vowels. Additionally, Przezdziecki (2005) found in his study on certain dialects of Yoruba vowels that [+ATR] front vowels are in general shorter than [–ATR] front vowels. In this study, several measurements were taken of Somali vowels testing for durational differences between vowels across the harmonic groups.

Using an α level of .05, an independent-samples t-test was conducted to evaluate whether vowel duration differed between phoneme pairs [i] vs. [ɪ], [e] vs. [ɛ], [æ] vs. [ɑ], [o] vs. [ɔ] and [u] vs. [ʊ] as a function of whether the phonemes were [±ATR]. The vowel durations for both [±ATR] phonemes followed a normal distribution and met the conditions for conducting a t-test. The test indicates significance ($p<0.05$) in three out of the five phoneme pairs. The t-test for the phoneme pair[i] vs [ɪ] was associated with a significant effect, $t(14) = 3.6$, $p = 0.005$. The t-test for the phoneme pair [e] vs [ɛ] was associated with a significant effect, $t(14) = 2.16$, $p = 0.048$. The t-test for the phoneme pair [æ] vs [ɑ] was associated with a significant effect, $t(7.4) = -2.43$, $p = 0.044$. As summarized in table 26 below, these three phoneme pairs demonstrate significance for vowel duration as a correlate.

Table 26

Results of Independent Samples t-test for Duration (ms)

Phoneme Pair	**Correlate**	**Mean Difference**	**t**	**df**	**p**
[i] vs [ɪ]	Duration	46	3.6	14	0.005√
[e] vs [ɛ]	Duration	21.1	2.16	14	0.048√
[æ] vs [ɑ]	Duration	-47.59	-2.43	**7.398**	0.044√
[o] vs [ɔ]	Duration	1.62	0.12	**14**	0.9
[u] vs [ʊ]	Duration	-7.06	-0.51	**14**	0.618

The individual speaker means below in Tables 27 and 28 indicate there is consistency between the speaker values for the three [ATR] pairs that demonstrated significance. In addition, there was consistency in the direction of the variation between the phonemes in each [ATR] pair.

Table 27

Duration - Male Speakers - Means and Standard Deviations

Duration	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	106	106	98	75	97	125	101	106	118	107
Speaker 2M	139	83	90	83	91	100	91	88	87	105
Speaker 3M	137	113	92	89	88	113	119	111	92	105
Speaker 4 M	128	94	110	87	101	121	104	110	111	112
Mean	128	99	98	84	94	115	104	104	102	107

Standard Dev.	13	11	8	5	5	10	10	9	13	3

Table 28

Duration - Female Speakers - Means and Standard Deviations

Duration	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	188	99	124	123	97	127	101	93	139	91
Speaker 2F	192	114	96	87	77	269	133	116	88	130
Speaker 3F	189	118	126	101	91	114	148	122	142	136
Speaker 4 F	144	126	157	80	108	163	144	183	142	189
Mean	**178**	**114**	**126**	**98**	**93**	**168**	**132**	**129**	**128**	**137**
Standard Dev.	**20**	**10**	**22**	**16**	**11**	**61**	**18**	**33**	**23**	**35**

Figures 10 and 11 below illustrate that duration was consistently longer for the vowels that demonstrated statistical significance. In Tables 29 and 30 below, the mean difference in lengths of the [+ATR] vowels were consistently greater for the [ATR] pairs that demonstrated significance for both male and female speakers.

The graph below in Figure 10 illustrates the differences in duration between phonemes in each [ATR] pair for male speakers. In the measurements above, the [+ATR] phonemes are longer in duration than their [-ATR] counterparts for vowel pairs [i] vs [ɪ] and [e] vs [ɛ]. The effect is reversed for [æ] vs [ɑ] and [u] vs [ʊ]. At 29 ms, the greatest difference in duration is observed between the [ATR] phoneme pair [i] vs [ɪ].

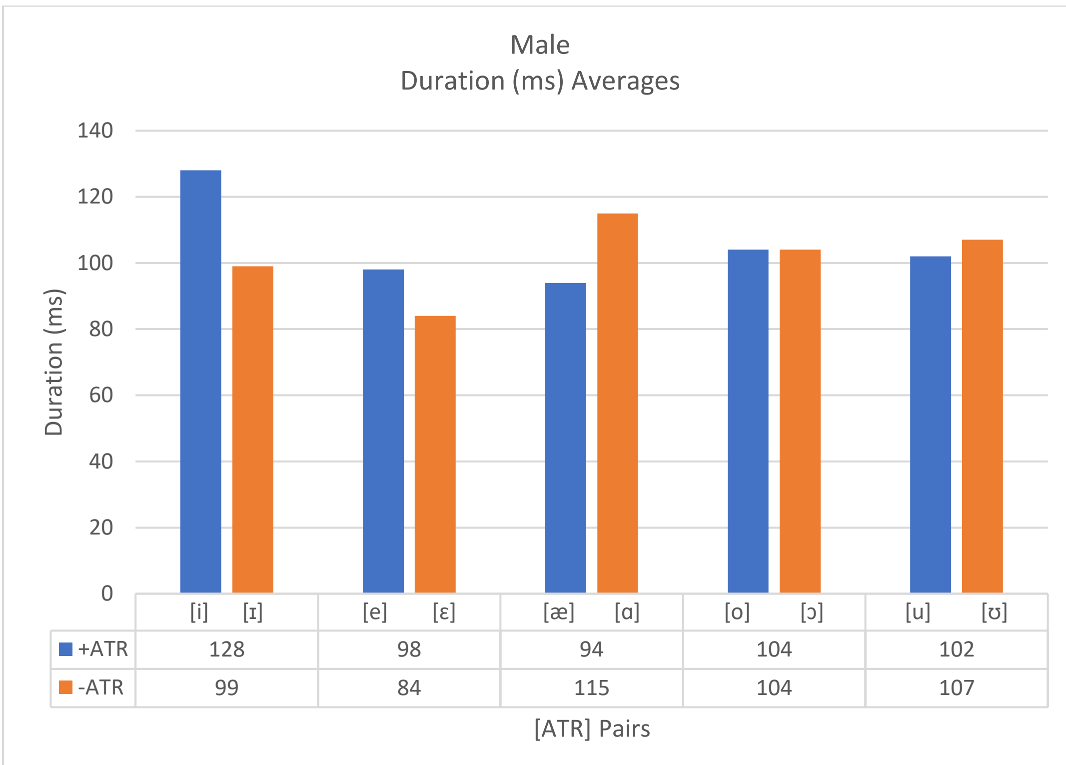

Figure 10 - Male Vowel Duration (ms) –Mean Values

The graph below in Figure 11 illustrates the differences in duration between phonemes in each [ATR] pair for female speakers. In the measurements above, the [+ATR] phonemes are longer in duration than their [-ATR] counterparts for vowel pairs [i] vs [ɪ], [e] vs [ɛ] and slightly longer for [o] vs [ɔ]. The effect is reversed for the other two phoneme pairs [æ] vs [ɑ] and [u] vs [ʊ]. At 64 ms, the greatest difference in means is observed between the [ATR] phoneme pair [i] vs [ɪ].

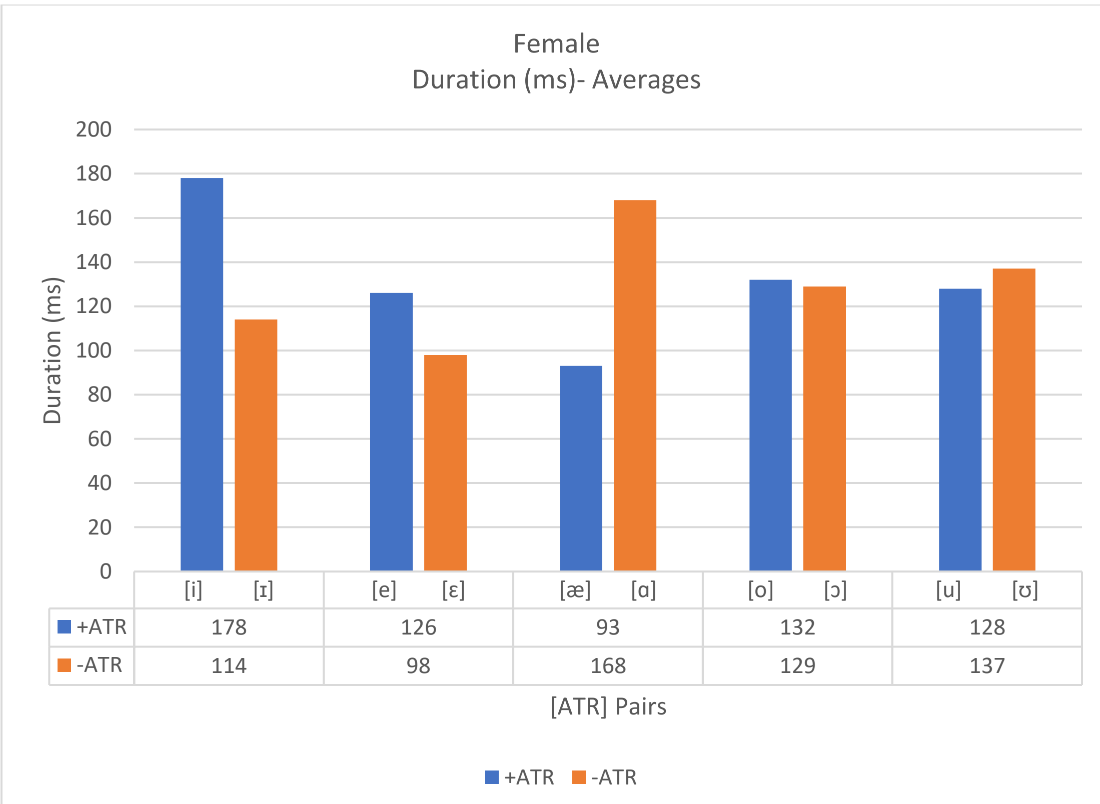

Figure 11 - Female Vowel Duration (ms) –Mean Values

Differences in Duration Means between Harmonic Pairs

[i] vs. [ɪ] for Duration

For male speakers, the mean duration of the [+ATR] phoneme **[i]** (M= 128 ms) was longer than the [-ATR] phoneme **[ɪ]** (M = 99 ms) by 29 ms. For female speakers, the mean duration of the [+ATR] phoneme **[i]** (M= 178 ms) was longer than the mean duration of the [-ATR] phoneme **[ɪ]** (M = 114 ms) by 64ms.

[e] vs. [ɛ] for Duration

For male speakers, the mean duration of the [+ATR] phoneme **[e]** (M = 98 ms) was longer than the mean duration of the [-ATR] phoneme **[ɛ]** (M = 84 ms) by 14ms. For female speakers, the mean duration of the [+ATR] phoneme **[e] (**M=126 ms) was longer than the mean duration of the [-ATR] phoneme **[ɛ]** (M = 98 ms) by 28 ms.

[æ] vs. [ɑ] for Duration

For male speakers, the mean duration of the [+ATR] phoneme **[æ]** (M=94 ms)was shorter than the mean value of [-ATR] phoneme **[ɑ]** (M = 115 ms) by 19 ms. For female speakers, the mean F3 value of the [+ATR] phoneme **[æ] (**M= 93 ms) was shorter than the mean value of the [-ATR] phoneme **[ɑ]** (M = 168 ms) by 75ms.

[o] vs. [ɔ] for Duration

For male speakers, the mean duration for the [+ATR] phoneme **[o]** (M=105 ms) was the same as the mean duration for the [-ATR] phoneme **[ɔ]** (M = 104s). For female speakers, the mean duration of the [+ATR] phoneme **[o] (**M= 132 ms) was longer than the mean duration of the [-ATR] phoneme **[ɔ]** (M = 129 ms) by 3 ms.

[u] vs. [ʊ] for Duration

For male speakers, the mean duration of the [+ATR] phoneme **[u]** (M= 102 ms) was shorter than the mean duration of the [-ATR] phoneme **[ʊ]** (M = 107 ms) by 5 ms. For female speakers, the mean duration of the [+ATR] phoneme **[u]** (M=128 ms) was shorter than the mean duration of the [-ATR] phoneme **[ʊ]** (M = 137ms) by 9 ms.

Table 29

Duration (ms) – Male – Summary of Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
Duration (ms)	128	99	98	84	94	115	104	104	102	107
Male Average Difference (ms)	**29**		**14**		**-19**		**0**		**-5**	

Table 30

Duration (ms) – Female – Summary of Mean Differences

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
Duration (ms)	178	114	126	98	93	168	132	129	128	137
Female Average Difference (ms)	**64**		**28**		**-75**		**3**		**-9**	

Chapter V: Discussion

The statistical tests run on the five vowel pairs [i] vs [ɪ], [e] vs [ɛ], [æ] vs [ɑ], [o]vs [ɔ] and [u] vs [ʊ] help inform our understanding of the significant correlates of [ATR] in the vowel system of Somali. Four of the correlates measured demonstrated statistically significant effects to varying degrees and for varying [ATR] pairs. The independent samples t-tests did not demonstrate a significant effect for F0. The t-tests demonstrated F1 to be the most significant correlate with four out of five [ATR] pairs having significant p-scores. F2 is a statistically significant correlate for two [ATR Pairs]. F3 is statistically significant for one [ATR] pair. Duration proved statistically significant for three [ATR] pairs.

F0 – Fundamental Frequency Saliency as a Correlate of [ATR]

Based on the findings of the t-tests summarized in Table 5, F0 is not a reliable correlate of the [+ATR] feature in Somali harmonic vowel pairs. In previous qualitative scholarship on the salience of F0 as a correlate of [ATR], the results have been inconsistent. Few studies have confirmed it is a reliable correlate of [ATR]. In the present study, the t-tests failed to confirm that differences in F0 values are statistically significant ($p < 0.05$) between the phonemes in each [ATR] vowel pair.

Even observation suggests that F0 is inconsistent for both male and female speakers. At times the front [+ATR] vowels are slightly longer and at other times they are not. The greatest acoustic distance in pitch was observed in [ATR] pair [i] vs. [ɪ] for both male and female speakers. For male speakers **[i]** (M=131 Hz) was lower than **[ɪ]** (M = 147 Hz) by 16 Hz. For female speakers, **[i]** (M= 208 Hz) was lower than **[ɪ]** (M = 245 Hz) by 37 Hz. While the pitch is lower in both cases, the t-tests fail to prove that it is a function of its [ATR] designation.

F1 Saliency as a Correlate of [ATR]

Based on the findings of the t-tests summarized in Table 8, F1 is the most reliable correlate of [ATR] for Somali harmonic vowel pairs. The F1 values for [+ATR] vowels are lower than their [-ATR] counterparts in [ATR] vowel pairs for both male and female speakers with the exception of [æ] vs [ɑ]. While [+ATR] vowels had lower F1 values, they have a higher point of articulation in the acoustic vowel space due to inverse proportionality. These findings are consistent with previous scholarship on the relationship between F1 and [ATR] (Lindau, 1978; Hess, 1992; Fulop et al, 1998; Guion et al, 2004; Anderson, 2007; Koffi, 2016). In addition to observational confirmation of consistently lower F1 values for all vowel pairs, a statistically significant ($p < 0.05$) effect was demonstrated for four of the five vowel pairs. However, for [æ] vs [ɑ], the t-test failed to demonstrate a significant effect ($p = 0.115$).

Significance was demonstrated for [i] vs [ɪ] at $p = 0.001$. The direction of the acoustic distance between these phonemes was the same for male and female speakers, however the difference in F1 distance between these phonemes for female speakers (M = 134 Hz) was greater than that of the F1 distance between these phonemes for male speakers (M = 109 Hz) by 25 Hz.

Significance was demonstrated for [e] vs [ɛ] at $p = 0.002$. The direction of the acoustic distance between these phonemes was the same for male and female speakers, however, the difference in F1 distance between these phonemes for female speakers (M = 139 Hz) was greater than that of male speakers (M = 108 Hz) by 31 Hz.

Significance was demonstrated for [o] vs [ɔ] at $p = 0.000$. The direction of the acoustic distance between these phonemes was the same for male and female speakers, however the difference in F1 distance for female vowels (M = 128 Hz) was higher than that of male speakers (M = 109 Hz) by 19 Hz.

Significance was demonstrated for [u] vs [ʊ] at p = 0.002. The direction of the acoustic distance between these phonemes was the same for male and female speakers. The mean differences in acoustic distance between these phonemes were roughly the same for both male (M = 73 Hz) and female (M = 74 Hz).

Significance was not demonstrated for [æ] vs [ɑ], at p = 0.115. The direction of the acoustic distance between these phonemes with [+ATR] vowels having higher F1s, was the same for male and female speakers. The mean differences in acoustic distance between these phonemes for both female speakers (M = 104 Hz) and male speakers (M = 108 Hz) were roughly the same.

The findings of F1 as the most salient correlate of [ATR] is consistent with studies on other African languages. Several previous statistical studies on the salience of F1 as a correlate of [ATR] (Starwalt, 2008; Kang and Ko, 2012; Quinn-Wriedt, 2013) confirm its strong relationship with [ATR]. Quinn-Wriedt (2013) performed a repeated measures ANOVA and confirmed varying degrees of significance for F1 as a correlate of [ATR] in another East African language, Maasai. It is also supported by previous theoretical and observational analyses (Ladefoged and Maddieson, 1996; Ladefoged and Johnson, 2015).

In addition, the other reason F1 exhibits such significant effects may be because the increase in size of the pharyngeal cavity, which results in a lower F1 frequency, isn't caused by just the advancement of the tongue root. It is also influenced by the raising of the tongue in the articulation of higher vowels. This is consistent with Lindau's findings in statistical tests on German and American vowels (1978). Lindau demonstrated that [+ATR] is in fact strongly correlated with tongue height:

"Three of the speakers have a high correlation between tongue height and advanced tongue root (Pearson's r = .90, 0.98, 0.80; p. < 0.01), one speaker has a moderate correlation (Pearson's r = 0.63; p < 0.01), and only one speaker has a very low correlation (Pearson's r = 0.21). So, for four out of five speakers, tongue-root advancement is not independent, but is in fact strongly related to tongue height." (1978; pp.558).

This dependent relationship between [ATR] and F1 poses a challenge in isolating the effect of [ATR] on vowels. The problem arises from the fact that F1 may vary due to both the advancement of the tongue root and the raising of the tongue body in the natural articulation of higher vowels. The degree to which it is due to [+ATR] is not a simple thing to answer. One correlate that shows potential in helping to distinguish the effect of [ATR] is F1 bandwidth. Hess (1992) showed that F1 bandwidth may be a may help in isolating the effect of ATR on F1 frequencies. This was confirmed by Anderson (2007) in his study on formant bandwidth.

F2 Saliency as a Correlate of [ATR]

Based on the findings of the t-tests summarized in Table 11, F2 is a reliable correlate in distinguishing between [ATR] designations for two Somali harmonic vowel pairs - [i] vs [ɪ] and [æ] vs. [ɑ]. While it is not as robust a correlate as F1, statistically, it is reliable for these two vowel pairs where significance ($p < 0.05$) was demonstrated. Observationally, the values for [+ATR] vowels were in general higher than their [-ATR] counter parts, but not always significantly so. Since the F2 values for [+ATR] vowels have higher frequencies, their point of articulation is more forward in the oral cavity and occupy a more fronted position in the acoustic vowel space. These findings support previous scholarship on the relationship between F2 and [ATR] (Lindau, 1978; Hess, 1992; Guion et al, 2004; Anderson, 2007).

It is important to note that while the other vowel pairs did not demonstrate significance based on the t-test, observationally the [+ATR] vowels had higher F2 frequencies in general. In all vowel pairs for male speakers, the [+ATR] vowels had higher F2 frequencies. In four of the 5 vowel pairs for female speakers the [+ATR] vowels had higher F2 frequencies with only [o] vs. [ɔ] exhibiting the opposite effect. Noting this, however, does not necessarily indicate that F2 is a more robust correlate than the statistical tests indicate.

The F2 values of the two [ATR] vowel pairs that demonstrated significance ([i] vs [ɪ] and [æ] vs. [ɑ]) show that the [+ATR] vowels are higher than their [-ATR] counterparts by between 191 Hz and 391 Hz with the lower difference being [æ] vs. [ɑ] for male speakers with an acoustic distance of 191Hz between these phonemes. Significance was demonstrated for [i] vs [ɪ] at $p = 0.003$. The direction of the acoustic distance between these phonemes was the same for male and female speakers, however, the mean difference in acoustic distance between female phonemes ($M = 385$ Hz) was greater than the mean difference in acoustic distance between male phonemes ($M = 248$ Hz) by 141 Hz. The [+High] [+Front] vowels for men have a shorter distance between [ATR] pairs than the female [ATR] vowel pairs.

Phoneme pairs [e] vs.[ɛ] had a mean acoustic distance of 186 Hz for male speakers and a mean acoustic distance of 21 Hz for female speakers. The t-test did not demonstrate significance. This may be explained by inconsistency in the variation and acoustic distance between F2 values for [e] vs.[ɛ] for all speakers. It also suggests that perhaps something besides, or in addition to, the forward movement of the tongue root is the source of the fronting of [e] in this case although Kang and Ko (2012) argue that it “is better associated with the pharyngeal cavity expansion rather than the actual tongue body raising” (pp.184).

Significance was demonstrated for [æ] vs [ɑ], at p = 0.017. The direction of the acoustic distance between these phonemes was the same for male and female speakers, however the difference in F1 distance for female vowels (M = 391 Hz) was considerably greater than that of male speakers (M = 191 Hz). In both cases [+ATR] vowels were higher in frequency than [-ATR] vowels.

Significance was not demonstrated for [u] vs [ʊ] (p = 0.32) as was the case for other African languages like Degema (Fulop et al, 1998). The test for [o] vs. [ɔ] also failed to demonstrate significance, and this pair had the lowest mean acoustic distances for both male and female speakers with a difference of 33 Hz for male speakers and -123 Hz for female speakers. The lack of significance for these two [+back] harmonic pairs is consistent with the findings of Kang and Ko (2012) in their analysis of these vowels for Tsongol Buriat, however, it is inconsistent with their finding on back vowels in Western Buriat. The lack of robustness for this correlate, especially with respect to the absence of a contrastive effect on some vowel pairs and not others is consistent with previous scholarship on F2 as a correlate (Fulop et al, 1998; Kang and Ko, 2012; Quinn-Wriedt, 2013; Koffi, 2016).

F3 Saliency as a Correlate of [ATR]

Based on the findings of the t-tests summarized in Table 14, F3 is not a reliable correlate in distinguishing between [ATR] designations for four of the five Somali harmonic vowel pairs. As observed in previous scholarship (Kang and Ko, 2012; Quinn-Wriedt, 2013), the F3 of a vowel has little relation to its [ATR] designation. However, unlike these two studies, significance in the differences between phoneme pairs was demonstrated for one vowel pair, [i] vs [ɪ] (p = 0.045).

For the only vowel pair that demonstrated statistical significance, the direction of the difference in acoustic distance for male and female vowels was the same with [i] having a higher F3 frequency than [ɪ] in both cases. The mean difference in acoustic distance between these phonemes was 351 Hz for male speakers and 206 Hz for female speakers. F3 appears to exhibit significance only for [+High] [+Front] vowels.

Furthermore, as illustrated in figures 8 and 9, the variation in frequency is small between the phonemes of many of the vowels in the different [ATR] sets. In addition, there is some inconsistent between male and female phoneme pairs in terms of the amount of acoustic distance and the direction. For example, the direction of the acoustic distance between [ATR] vowel pair [e] vs.[ɛ] is the same for male and female vowels with [e] having a higher F3 value than [ɛ] for both male and female speakers, but the *amount* of acoustic distance between female phonemes is almost seven times greater than the *amount* of acoustic distance between male phonemes. A similar inconsistency is observed for the [ATR] vowel pairs [o] vs. [ɔ] and [u] vs [ʊ]. The statistical tests and the observations of formant values fail to show that the [ATR] designation of a vowel is correlated with F3.

Duration Saliency as a Correlate of [ATR]

Based on the findings of the t-tests summarized in Table 17, duration is significant for three Somali harmonic vowel pairs: [i] vs [ɪ] ($p = 0.005$), [e] vs [ɛ] ($p = 0.048$) and [æ] vs [ɑ] ($p = 0.044$). Out of these pairs, the duration for [+Front] [+ATR] vowels [i] and [e] are longer than their [+Front] [-ATR] counterparts [ɪ] and [ɛ] for both male and female vowels. While there is statistical confirmation of significant differences between [ATR] pairs [i] vs [ɪ] ($p = 0.005$), [e] vs [ɛ] ($p = 0.048$) and [æ] vs [ɑ] ($p = 0.044$), the direction of the difference for [æ] vs [ɑ] exhibits a different pattern with the [-ATR] vowel having a longer duration for both male and female speakers. These findings support previous scholarship on the importance of duration in distinguishing between [ATR] vowel pairs (Hess, 1992; Guion et al, 2004; Przezdziecki, 2005; Aralova et al, 2011).

What emerges is that the significance of duration between [ATR] pairs in this study differs from previous studies in at least two ways: the direction of the differences and the location of the vowels exhibiting significant durational differences. As illustrated in figures 10 and 11, inconsistent effects are observed for the direction of the acoustic distance [æ] vs [ɑ]. For female vowels the mean duration of [ɑ] was longer than [æ] by 75 ms. For Male vowels the mean duration of [ɑ] was longer than [æ] by 19 ms. This presents the first difference from previous studies. Whereas Przezdziecki (2005) found that [+front] [+ATR] vowels are shorter in duration than [+front][-ATR] in some dialects of Yoruba, the front vowels in this study exhibit the opposite effect for both male and female speakers with the exception of [æ] vs [ɑ]. The second difference between these results and previous studies is that for the [+back] vowel pairs [o] vs [ɔ] and [u] vs [ʊ], duration was neither statistically significant nor observationally consistent. This is inconsistent with the results of Guion et al (2004) where back vowels exhibited significant durational variation between [ATR] sets. It is also inconsistent with Starwalt's (2008) findings that there was no apparent pattern between [ATR] and duration.

While several vowel pairs demonstrated durational significance ($p < 0.05$), perhaps the significance would be different if the measurements of duration were done separately from formant measurements. The challenge emerges from the fact that the area of measurement is artificially shortened to counter co-articulatory effects of adjacent segments. The shortening is due to an attempt to measure only the steady state of a given vowel. This is optimal when searching for the formant frequencies or decibels of a certain portion of the sound wave. In such cases the shortening doesn't affect accuracy in measurements, but rather increases it. However, when measuring the *length* of the vowel segment itself, measuring into the vowel for even 20ms can potentially impact the results. Perhaps choosing the least invasive adjacent vowels would help, but even in that case, that would present inaccurate values for the length of the vowel.

Chapter VI: Conclusion

The experiments in this paper were designed to empirically describe the acoustic correlates of Somali vowel harmony with respect to [ATR]. A series of statistical tests were conducted to analyze five acoustic correlates in Somali which is a language known to have [ATR] Vowel Harmony. Using the standard dialect of Somali, 240 tokens were analyzed from four male speakers and four female speakers. The independent samples t-tests confirmed four of the hypotheses to varying degrees: F1 is consistently greater for [+ATR] vowels except for [æ] vs [ɑ]; F2 is significantly greater for only [i] vs [ɪ] and [æ] vs [ɑ]. F3 is significantly greater only for [i] vs [ɪ], and duration is significant for [i] vs [ɪ, [e] vs [ɛ] and [æ] vs [ɑ]. With F0 demonstrating no significant effects across all harmonic pairs, this study provides us with four findings.

The first confirmation, that F1 is the most reliable of the correlates of [ATR] is not surprising. This is a consistent finding across studies in [ATR] vowel harmony research (Lindau, 1978; Hess, 1992; Fulop et al, 1998; Guion et al, 2004; Anderson, 2007; Starwalt, 2008; Kang and Ko, 2012; Quinn-Wriedt, 2013; Koffi, 2016). The statistical significance of F1 as a correlate is due in part to the dependent relationship between the raising of the tongue and the advancement of the tongue root. Further research is required to determine the degree to which the raising of the tongue and the advancement of the tongue root are correlated and to which degree either produces variations in F1 frequencies for Somali vowels.

The second finding that F2 is not a robust cue for distinguishing between harmonic pairs is also not unexpected. While it demonstrates statistical significance for only two vowel pairs, the data suggests that with only one exception, [+ATR] vowels are generally more fronted than [-ATR] vowels. This is consistent with similar results in previous studies that conclude its weakness as a correlate (Fulop et al, 1998; Kang and Ko, 2012; Quinn-Wriedt, 2013).

The third finding is that F3 is not a robust cue for distinguishing between harmonic pairs. The statistical tests failed to demonstrate significance for all but one set of [ATR] harmonic pairs: [i] vs [ɪ]. As quoted by Kang and Ko (2013), early studies on F3 suggested that it was perhaps related to the pharyngealization in the articulation of certain vowels. This helps explain the significant effect of F3 on the [+High] [+ATR] vowel pair [i] vs [ɪ] and its lack of significance between phonemes in the other harmonic pairs.

Finally, duration has proven to be a reliable correlate for three of the harmonic pairs. This finding was perhaps the most interesting in that it was both consistent and inconsistent with previous studies (Hess, 1992; Guion et al, 2004; Przezdziecki, 2005; Aralova, Grawunder, & Winter, 2011). It was consistent with some studies in its significance as a correlate, however it differed from other studies in the direction of the variation in acoustic distance between harmonic pairs and in which harmonic pairs that demonstrated significance.

With the statistical confirmation of several acoustic measurements as correlates and the lack of confirmation for others, the degree to which the [ATR] designation of particular vowels initiates or participates in the change in value and/or the direction of the change in value requires further investigation. Furthermore, while the statistical results don't indicate significance for some correlates in some harmonic pairs, the inconsistency in the variation for some of the harmonic pairs allows room for other correlates to explain the observed phenomena.

Several themes and questions have emerged in this study. The first theme is that the [+High] [+ATR] harmonic vowel pair [i] vs [ɪ] tends to have the most consistency in a significant effect being demonstrated by the correlates measured. The question to be answered here is what are the unique features of this harmonic pair that make its formant frequencies and vowel durations so consistently correlated with [ATR]?

The second theme is that with respect to [ATR] several correlates have more cross linguistic consistency than others: F1, F0 and F3. The variations observed for these correlates across the harmonic pairs are consistent with previous studies with F1 being consistent with other [ATR] harmony languages in its salience and F0 and F3 being consistent in their lack of significance. F2 and duration, however, seem to lack cross linguistic consistency. The question to be answered here is what is the source of the departure from other languages in the direction of variation in the measurements and or relevant vowel pairs for F2 and duration?

Limitations of the Study

This study isn't without some limitations, which, if resolved, may help answer some of the questions raised above. Durational measurements require note in this respect. There may be an effect on this correlate as a result of seeking the steady state of a vowel to reduce the coarticulatory effects of adjacent segments. Perhaps the effect of [ATR] on duration would be better represented if it was measured separately from other correlates. The full vowel may be measured without adjusting the measurement of the sound wave to account for co-articulatory effects. In such a case the vowel would be measured from the beginning or closer to the beginning of the segment. In this study, the assumption was that its accuracy in measurements would be higher if the same segment was used for each correlate. The adjustment for the measurement of vowel duration would have invalidated the results of the other correlates. Perhaps that explains the mixed results in the significant effect of duration on distinguishing between [ATR] pairs. In future studies, analysis of duration may be better served as a standalone study.

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Appendix A

Male Speaker Summary of Means

Mean Values Summary - Male Speakers - All Phonemes – All Variables

Phoneme	**[i]**	**[ɪ]**	**[e]**	**[ɛ]**	**[æ]**	**[ɑ]**	**[o]**	**[ɔ]**	**[u]**	**[ʊ]**
ATR	+	-	+	-	+	-	+	-	+	-
F0 (Hz)	131	147	155	146	139	144	163	149	167	164
F1(Hz)	306	415	475	583	761	653	481	590	381	454
F2(Hz)	2173	1925	1934	1752	1512	1321	1071	1038	1074	962
F3(Hz)	2913	2562	2434	2458	2429	2402	2268	2572	2305	2446
Duration (ms)	128	99	98	84	94	115	104	104	102	107

Appendix B

Female Speaker Summary of Means

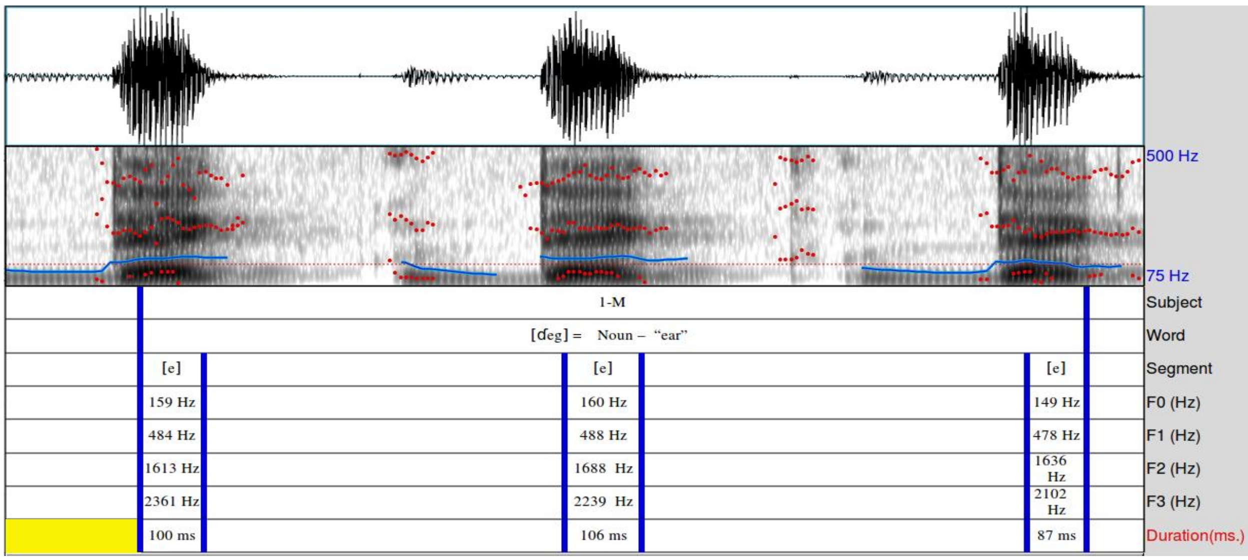
Mean Values Summary - Female Speakers - All Phonemes – All Variables

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
ATR	+	-	+	-	+	-	+	-	+	-
F0 (Hz)	208	245	224	236	208	222	242	226	264	242
F1(Hz)	351	485	559	698	862	758	546	674	425	499
F2(Hz)	2497	2112	2092	2071	1850	1459	1074	1197	1212	1148
F3(Hz)	3105	2899	2760	2936	2680	2749	2790	2808	2785	2821
Duration (ms)	178	114	126	98	93	168	132	129	128	137

Appendix C

Male Spectrogram Sample

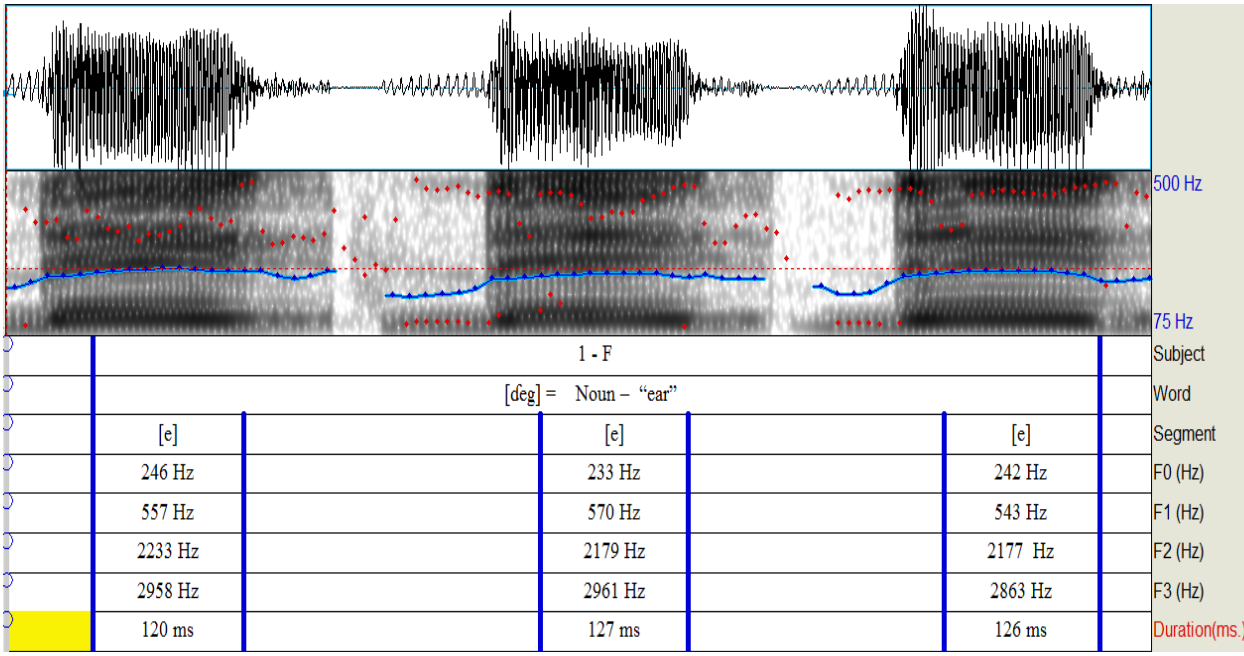
Male Speaker 1M – Sample Spectrogram Segment Delineation Procedure



Appendix D

Female Spectrogram Sample

Female Speaker 1F – Sample Spectrogram Segment Delineation Procedure



Appendix E

Corpus of Recorded Speech Sounds Selected for Spectrogram Analyses

No.	1	2	3	4	5	6	7	8	9	10
Lexical Items	/dɪs/	/bijow/	/dɛx/	/deg/	/dar/	/ʔaeb/	/tɔl/	/fog/	/dʊl/	/gun/
Meaning	Build	Water	Middle	Ear	Clothes	Drink	Sew	Far	Ground	Well bottom
Vowels	[i]	[ɪ]	[ɛ]	[e]	[a]	[æ]	[ɔ]	[o]	[ʊ]	[u]

Appendix F

10 Individual Speaker Value Tables and Standard Deviations – All Variables

F0 Male Speakers - Means and Standard Deviations

Phoneme	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	130	150	156	156	133	149	156	149	156	151
Speaker 2M	100	123	120	121	106	110	123	123	142	138
Speaker 3M	122	138	140	121	139	127	159	151	164	153
Speaker 4 M	173	176	204	185	176	189	212	173	207	212
Mean	**131**	**147**	**155**	**146**	**139**	**144**	**163**	**149**	**167**	**164**
Standard Dev.	**26**	**19**	**31**	**27**	**25**	**30**	**32**	**18**	**24**	**29**

F0 - Female Speakers - Means and Standard Deviations

F0	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	229	265	240	252	210	227	239	216	317	253
Speaker 2F	203	271	235	257	230	241	255	235	269	248
Speaker 3F	199	198	219	219	207	205	234	219	240	245
Speaker 4 F	202	247	202	215	184	214	239	235	231	220
Mean	**208**	**245**	**224**	**236**	**208**	**222**	**242**	**226**	**264**	**242**
Standard Dev.	**14**	**33**	**17**	**22**	**19**	**16**	**9**	**10**	**39**	**15**

F1 - Male Speakers - Means and Standard Deviations

F1	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	268	397	483	523	750	609	479	556	377	430
Speaker 2M	276	413	494	617	828	733	514	635	378	486
Speaker 3M	410	434	459	575	785	631	484	601	353	465
Speaker 4 M	268	414	463	615	679	639	448	567	415	435
Mean	**306**	**415**	**475**	**583**	**761**	**653**	**481**	**590**	**381**	**454**
Standard Dev.	**60**	**13**	**14**	**38**	**55**	**47**	**23**	**31**	**22**	**23**

F1- Female Speakers - Means and Standard Deviations

F1	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	419	533	557	737	834	850	564	683	376	511
Speaker 2F	334	503	528	757	692	487	527	660	452	492
Speaker 3F	275	401	541	654	914	902	540	658	385	488
Speaker 4 F	377	504	608	643	1009	792	552	693	485	505
Mean	**351**	**485**	**559**	**698**	**862**	**758**	**546**	**674**	**425**	**499**
Standard Dev.	**53**	**50**	**30**	**50**	**116**	**161**	**14**	**15**	**46**	**9**

F2 - Male Speakers - Means and Standard Deviations

F2	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	2101	1791	1646	1666	1407	1196	1007	1008	995	913
Speaker 2M	2177	1965	2018	1788	1508	1359	1128	978	1058	869
Speaker 3M	2241	1838	1983	1635	1768	1442	1126	1118	1169	1113
Speaker 4 M	2171	2106	2088	1917	1365	1287	1021	1048	1074	951
Mean	**2173**	**1925**	**1934**	**1752**	**1512**	**1321**	**1071**	**1038**	**1074**	**962**
Standard Dev.	**50**	**122**	**170**	**111**	**157**	**91**	**57**	**52**	**62**	**92**

F2 - Female Speakers - Means and Standard Deviations

F2	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	2552	2189	2196	2195	1757	1627	1078	1211	1237	1206
Speaker 2F	2655	2227	2154	2078	1985	1059	1160	1316	1143	1219
Speaker 3F	2364	2073	2005	2091	1845	1493	954	1077	905	964
Speaker 4 F	2415	1958	2012	1918	1813	1657	1104	1182	1563	1201
Mean	**2497**	**2112**	**2092**	**2071**	**1850**	**1459**	**1074**	**1197**	**1212**	**1148**
Standard Dev.	**114**	**105**	**85**	**99**	**84**	**239**	**75**	**85**	**236**	**106**

F3 Male Speakers - Means and Standard Deviations

F3	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	2672	2415	2234	2387	2522	2555	2253	2685	2367	2442
Speaker 2M	3008	2455	2371	2309	2214	2223	2070	2368	2142	2443
Speaker 3M	3056	2715	2493	2635	2590	2280	2382	2636	2304	2402
Speaker 4 M	2914	2661	2638	2500	2390	2549	2366	2598	2405	2495
Mean	**2913**	**2562**	**2434**	**2458**	**2429**	**2402**	**2268**	**2572**	**2305**	**2446**
Standard Dev.	**148**	**129**	**149**	**123**	**143**	**152**	**125**	**122**	**101**	**33**

F3 - Female Speakers - Means and Standard Deviations

F3	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	3113	3170	2927	3224	3212	3264	2931	3090	2988	2788
Speaker 2F	3543	2787	2563	3039	2336	2500	2660	2374	2683	2764
Speaker 3F	2753	2729	2646	2607	2347	2372	2618	2592	2754	2811
Speaker 4 F	3011	2911	2904	2872	2826	2860	2952	3175	2715	2921
Mean	**3105**	**2899**	**2760**	**2936**	**2680**	**2749**	**2790**	**2808**	**2785**	**2821**
Standard Dev.	**285**	**170**	**158**	**227**	**365**	**347**	**152**	**335**	**120**	**60**

Duration - Male Speakers - Means and Standard Deviations

Duration	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1M	106	106	98	75	97	125	101	106	118	107
Speaker 2M	139	83	90	83	91	100	91	88	87	105
Speaker 3M	137	113	92	89	88	113	119	111	92	105
Speaker 4 M	128	94	110	87	101	121	104	110	111	112
Mean	**128**	**99**	**98**	**84**	**94**	**115**	**104**	**104**	**102**	**107**
Standard Dev.	**13**	**11**	**8**	**5**	**5**	**10**	**10**	**9**	**13**	**3**

Duration - Female Speakers - Means and Standard Deviations

Duration	[i]	[ɪ]	[e]	[ɛ]	[æ]	[ɑ]	[o]	[ɔ]	[u]	[ʊ]
Speaker 1F	188	99	124	123	97	127	101	93	139	91
Speaker 2F	192	114	96	87	77	269	133	116	88	130
Speaker 3F	189	118	126	101	91	114	148	122	142	136
Speaker 4 F	144	126	157	80	108	163	144	183	142	189
Mean	**178**	**114**	**126**	**98**	**93**	**168**	**132**	**129**	**128**	**137**
Standard Dev.	**20**	**10**	**22**	**16**	**11**	**61**	**18**	**33**	**23**	**35**

Appendix G

Participant Sociometric Background Questionnaire for Participant Selection

1) What is your native language?
2) Was that language the primary language used in your household through adolescence?
3) Is that still the language you use most frequently and feel you are the most fluent in?
4) What part of your native country are you from?
5) What dialect do you speak?
6) At what age did you leave your hometown to live abroad?
7) What is your current age?