ABSTRACT

AN ACOUSTIC ANALYSIS OF THE FEATURE ADVANCED TONGUE ROOT IN KARAJÁ

Recent phonological analysis of Karajá, a Macro-Jê language of Brazil, claimed that the language's vowel system evinces advanced tongue root (ATR) harmony (Ribeiro 2001). Despite this, the phonetic facts about these vowels have never been published, which has left the only claim that ATR operates in any American language subject to controversy. The use of tongue root advancement can never be completely established without articulatory investigation (e.g., MRI scan), but I here provide an acoustic analysis of two native Karajá speakers, which examines the correlates of [ATR/RTR] in four pairs of vowels. An ATR vowel involves expansion of the pharyngeal cavity by moving the base of the tongue forward and/or lowering the larynx during vowel production, and in the case of an ATR harmony language, contrasts with a retracted [RTR] version of the vowel. Acoustic correlates of tongue root advancement generally include a lowering of the frequency of F_1 as the pharyngeal cavity expands, some change in F_2, and changes in spectral timbre as measured by the relative formant amplitudes. Particularly, the amplitude of F_1 is considerably greater in [ATR] vowels when compared with [RTR] vowels (Fulop et al. 1998), and this will be used to illuminate the phonological claims

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AN ACOUSTIC ANALYSIS OF THE FEATURE ADVANCED TONGUE ROOT IN KARAJÁ

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CHAPTER 1: INTRODUCTION

The vocalic systems of some languages are divided into two sets distinguished by their participation in a process of vowel harmony wherein only members of one vowel class or the other may co-occur within a phonological word, group of morphemes, or some other domain. One feature which may form the basis of such a harmony system is ADVANCED TONGUE ROOT (ATR), first described in members of the Niger-Congo and Nilo-Saharan languages of Africa. Akan presents a prototypical and uncontroversial case of a nine-vowel, five-height ATR harmony, as described by Casali (2003) with the vowels /i ɪ e ɛ o ɔ u ʊ/ contrasting along the feature [ATR], and the low vowel /a/ a nonparticipant in the process. Casali reports in his case study that in such nine-vowel systems [ATR] vowels are dominant over [RTR] vowels— that is, it is the [ATR] feature which spreads, though this is not the only possible arrangement, as Casali notes that seven-vowel ATR systems which demonstrate harmony only among the mid-vowels tend to be [RTR] dominant. The phonetic features that distinguish [ATR] from [RTR] vowels have been researched most comprehensively in African languages, and are discussed in the following section, *The Phonetics of the feature [ATR]*, below.

While the ATR feature was once thought to be limited to the languages of West Africa (Stewart 1967), it has since been included in the analysis of some north-east Asian languages in the purported Altaic family— specifically within the Mongolic and Tungusic branches (van der Hulst & Smith 1988, Svantessen et al. 2005, Ko 2012). Further, phonetic analysis of three Altaic languages confirms acoustic correlates consistent with those of tongue root features in West African languages (Aralova et al. 2011, Kang & Ko 2012), as reviewed in the following section.

This study will present an acoustic examination of the vocalic system of the Brazilian isolate Karajá— which is sometimes positioned as a member of the purported Macro-Jê family (cf. Ribeiro 2000, Rodrigues 1999)— in light of recent claims that the vowel harmony described therein is an example of five-height ATR harmony (Ribeiro 2000). While Karajá has more contrastive vowels than a nine-vowel system such as Akan, not all of them participate in the harmony process, much like the low vowel of a prototypical nine-vowel system. The examples in 1a-b, taken from Ribeiro (2000), demonstrate the harmony process in Karajá, whereby an [ATR] vowel in a morpheme overrides any leftward [RTR] vowels.

(1) a.	/wa-ritʃɔrɛ	rʊ/	[waritʃɔrɛrʊ]
	1-offspring	thigh	
	‘my child’s thigh’		
b.	/wa-ritʃɔrɛ	dʒ-u/	[waritʃoredʒu]
	1-offspring	rel-tooth	
	‘My child’s tooth’		

While vowel harmony in Karajá is consistent and documented, a lack of examination of the phonetic facts about the vowels of Karajá has left the only claim of an ATR distinction in a language of the Americas in controversy.

The Phonetics of the Feature [ATR]

Some early descriptions of a number of West African languages which would later come to be described as possessing ATR harmony resulted in the adoption of ‘tense/lax’ terminology to describe the relationship between the vowels of the two sets, along with the observation that vowel harmony seemed to be a process of assimilation causing all co-occurring vowels to agree in some parameter (Stewart 1967), although the precise nature of this parameter was elusive. Observation of Ladefoged's (1964) cineradiographic tracings of Igbo speakers led to Stewart's eventual description of the tongue root manipulation, which came to be described as the feature [ATR].

Articulatory Correlates of the Feature [ATR]

The articulatory basis of ATR has been studied through the use of both cineradiography (Lindau 1972, 1979) and more recently through the use of magnetic resonance imaging (MRI) (Teide 1996). In each case, it was found that the articulation of [ATR] vowels was distinct in more than simple movement of the tongue root. Lindau proposed a renaming of the feature to 'expanded' on the basis of an observed lowering of the larynx in addition to the movement of the tongue root, while Tiede reported a concomitant transverse expansion of the pharyngeal cavity in addition to the sagittal movement of the tongue root. Further, Teide described the retracted [RTR] vowels of Akan as occurring with marked constriction of the pharyngeal cavity through the action of the medial pharyngeal constrictors.

Acoustic Correlates of the Feature [ATR]

Due to the manipulation of the size of the pharyngeal cavity, a number of acoustic correlates are expected for ATR contrasts. The earliest identified and most widely confirmed acoustic correlate of an ATR distinction is found in the frequency of the first formant. Due to the increase in the volume of the back cavity of the pharynx during [ATR] articulations, Halle and Stevens (1969) predicted a lowering of the frequency of F_1, which has since been observed in the [ATR] vowels of Niger-Congo languages Akan (Lindau 1978) and Degema (Fulop et al. 1998), Nilotic languages DhoLuo, Shilluk (Jacobson 1980), and Maa (Guion et al. 2004), and most recently in the Altaic languages Ewen (Aralova et al. 2011, Kang & Ko 2012), Western Buriat, and Tsongol (Kang & Ko 2012).

The frequency of the second formant is likewise seen to vary between [ATR] and [RTR] vowels, although of difference is not regular cross linguistically— and even within languages, F_2 changes occur in disordinal patterns, i.e. unlike the general lowering of F_1 frequency across all vowels, relative F_2 values tend to vary according to vowel position. Jacobson (1980) found that the [RTR] vowels in the Nilotic languages DhuLuo and Shilluk occupy more peripheral positions than their [ATR] counterparts. That is, [RTR] front vowels in these languages have higher F_2 frequencies than corresponding [ATR] vowels, while the [RTR] back vowels possess lower F_2 values. Fulop et al. (1998) found that the opposite relationship exists in Degema, however, as [ATR] vowels in this language are more peripheral than the [RTR] equivalents. Thus, while it is clear that differences in F_2 can correspond to [ATR] distinctions, there is no clear cross linguistic pattern.

In addition to the frequencies of the first and second formants, a growing body of evidence indicates that SPECTRAL TIMBRE is an important acoustic correlate of ATR distinctions. It is often noted in ATR literature that [ATR] vowels sound deeper, hollow, or breathier than [RTR] vowels, which are in turn described as brighter, brassy, or creaky (Berry 1955, Stewart 1967, Jacobson 1980). Beyond impressionistic auditory qualities, the use of the terms breathy and creaky indicate actual differences in phonation type, which have been documented to occur in some ATR systems, but by no means all (Kingston 1997). Karajá, like many other languages with purported ATR contrasts, carries no impressionistic sign of any such breathy/creaky alternation. However, differences in phonation type are by no means the only method of accounting for the perceptual difference in quality between [ATR] and [RTR] vowels, nor are changes in phonation the only means of accounting for differences in spectral timbre.

The auditory impressions of [ATR] and [RTR] vowel differences have been shown to be related to the overall shape of the spectrum, with [ATR] vowels possessing more energy in the lower frequencies of their spectra, while higher frequency energy contributes relatively more to the spectra of [RTR] vowels. Hess (1992) found that the [ATR] vowels of Akan had higher F_1 amplitudes than [RTR] vowels, though she was limited to comparing vowel pairs with comparable formant frequencies (i.e. /ɪ/ & /e/, and /ʊ/ & /o/), due to the fact that formant amplitude is correlated with formant frequency, as shown by Fant (1960). In order to account for this correlation between formant frequency and amplitude, Fulop et al. (1998) developed a normalization process to minimize the variation caused by vocal tract resonances and thus analyze the complete vowel system of Degema, finding that high frequency energy accounts for a relatively greater portion of the spectra of [RTR] vowels. This normalization procedure is used in the present study in order to compare the relative differences in spectral timbre between the two sets of Karajá vowels.

There are a number of potential explanations for the differences in spectral timbre in ATR systems in addition to the phonation differences discussed above. First, isometric tension can change the damping qualities of the vocal apparatus, as a greater degree of tension, and thus stiffness, in the pharyngeal cavity would lead to less dissipation of acoustic energy (i.e. damping) than in a more lax articulation (Tiede 1996). Second, the pharyngeal constriction of [RTR] vowels can lead to friction damping in the vicinity of F_1 as discussed by Fulop et al. (1998).

CHAPTER 2: THE [ATR] DISTINCTION IN KARAJÁ

Karajá is a Macro-Jê language spoken by the Karajá people in the vicinity of the Araguaia River in Brazil. While a number of Karajá dialects exist, the data in the present study come from two speakers of the South Karajá dialect.

Even before the considerations of an ATR distinction, the precise number of vowels in Karajá seems to be subject to some disagreement. Analysis by Rodrigues (1999) follows Fortune (1973) and places the number of vowels at eleven, with nine oral and two nasal vowels. Ribeiro (2000) revises this into a count of fourteen vowels, with eleven oral vowels, and three nasals. The two competing vowel charts are shown in Table 1.

Table 1. Two Purported Vocalic Inventories of Karajá

Rodrigues (1999)			Ribeiro (2000)		
i	ɨ	u	i, ĩ		u
e	ə, ə̃	o, õ	ɪ	ɨ	ʊ
ɛ	a	ɔ	e	ʌ	o, õ
			ɛ	ə̃	ɔ
				a	

Ribeiro claims the basis for his reorganization is the [ATR] feature, which divides the vowels of Karajá into three classes: [ATR], [RTR], and opaque, the latter blocking regressive ATR harmony. Table 2 shows these divisions.

Table 2. Categorical ATR Divisions in Karajá Following Ribiero (2000)

[ATR]			Opaque			[RTR]		
i		u	ĩ			ɪ	ɨ	ʊ
e	ʌ	o		ə̃	õ	ɛ		ɔ
				a				

While the front and back, close and mid vowels participate as counterparts of one another in Ribeiro's ATR system, the two non-opaque central vowels are not counterparts of one another. Ribeiro's argument seems to be that the [RTR] close central vowel /ɨ/ has a separate, barely distinguished [ATR] form not included in his vowel inventory, as seen in example 2, taken from Ribeiro (2000).

(2) /r-ɛ-kɨ-re/ [rekɨ̘re]

ctfg-1.trans-eat.grains-ctfg-imperf

'I ate it'

In this analysis, [ɨ̘] is an [ATR] version of /ɨ/, which is largely transparent to the process of vowel harmony, though Ribeiro reports that native Karajá speakers intuit that /ɨ/ seems 'stronger' in [ATR] contexts.

CHAPTER 3: METHODS AND MEASUREMENTS

The data analyzed in this study were collected from two native speakers of the South Karajá dialect. Speaker 1 is a male in his thirties from the village of Santa Isabel do Morro, where his interview took place. Speaker 2 is a female in her mid-twenties from the village of São Domingos. Her interview took place at the Federal University of Goiás in the city of Goiânia. The data consist of nonsense words of three shapes, each a combination of a vowel and the glottal fricative /h/ as listed in Table 3.

Table 3. Karajá Nonsense Words

	Model 1	Model 2	Model 3
1.	hi	ihi	hii
2.	hɪ	ɪhɪ	hɪɪ
3.	he	ehe	hee
4.	hɛ	ɛhɛ	hɛɛ
5.	ha	aha	haa
6.	hʌ	ʌhʌ	hʌʌ
7.	hɨ	ɨhɨ	hɨɨ
8.	hu	uhu	huu
9.	hʊ	ʊhʊ	hʊʊ
10.	ho	oho	hoo
11.	hɔ	ɔhɔ	hɔɔ

Note. Some targets are actual words, such as *hɛɛ* ‘firewood’, *ɨhɨ* ‘wind’, and *ɔhɔ* ‘mosquito’.

Formant Frequencies

The frequencies of the first, second, and third formants were measured at one third of the duration of each vowel token using the Praat phonetic analysis software, version 5.3.63 (Boersma & Weenink 2014). The onset of each vowel was determined to coincide with the first full glottal pulse, and the offset with the final glottal pulse corresponding with visible F_2 energy. The peaks reported by the formant finding algorithm were recorded, except in the few cases where the LPC peaks were obviously misaligned on visual inspection, or clearly spurious measurements (e.g. an F_2 measurement of 500Hz for a token of the vowel /u/). In these cases, the temporal location of the measurement was adjusted forward in 10ms increments until a well-aligned, non-spurious measurement was produced.

Because of the difficulties inherent to the automated formant tracking of nasal vowels due to the nasal formants, coupled with the opacity of the nasal vowels in Karajá's ATR system, the nasal vowels are not considered in this analysis.

Spectral Timbre

In order to compare the spectral timbre of [ATR] and [RTR] vowels, the normalization procedure using the amplitudes of the first and second formants (A1 and A2) described by Fulop et al. (1998) was used. In this method, a modeled amplitude for each measured formant was calculated using a vocal tract model assuming a fixed bandwidth and glottal pulse using equations from Fant (1960). The formula in 3 calculates the contribution of a single formant to the spectrum of a vowel, where F is a resonant frequency for the formant (F_1, F_2, F_3), and b is the bandwidth of the formant (30Hz for F_1, 80Hz for F_2, and 150 Hz for F_3).

(3)
$$dB(f) = 20\log_{10} \frac{F^2 + (b/2)^2}{\sqrt{(f-F)^2 + (b/2)^2} \times \sqrt{(f+F)^2 + (b/2)^2}}$$

To the sum of the three curves created by this equation, the contributions of higher formants must be added using the equation in 4, in order to account for the contributions of formants higher in the spectrum.

(4) $dB(f) = 0.72(f / 492)^2 + 0.0033(f / 492)^4$

Finally, the spectral contribution of the glottal pulse was calculated using the equation in 5, where g is the contribution of phonation type (g=1 here).

(5) $$dB(f) = g\left(-20\log_{10}\left(2\frac{f/100}{1+(f/100)^2}\right)\right)$$

The resulting modeled A_2 value for each vowel was then subtracted from the modeled A_1 value. This modeled A_1-A_2 value is then subtracted from the observed value of A_1-A_2. The observed A_1 and A_2 of each vowel token was measured through the analysis of a long term average spectrum (LTAS) generated in Praat for each vowel token. The frequency of F_1 and F_2 were measured as described in the above section, and A_1 and A_2 were measured at these frequencies. The resulting normalized A_1-A_2 values reveal differences in spectral slope assumed to be caused by actual changes in phonation or bandwidth, rather than occurring automatically through the nature of the vocal tract and the frequencies of the formant values.

The amplitude measurement process and normalized A_1-A_2 calculations in the present study were performed using a version of a Praat script by Mills (2009) reproduced in the Appendix.

CHAPTER 4: RESULTS AND ANALYSIS

Figures 1 and 2 are standard plots of F_1 and F_2 for each speaker. In considering these formant plots, it is clear that [ATR] vowels have generally higher F_1 values than their [RTR] counterparts, although the relationship is less pronounced in the high vowels of speaker 2. Further, the central [ATR] vowels are noticeably more peripheral than their [RTR] counterparts. In the case of the two non-low central vowels, /ɨ/ and /ʌ/, no particular pattern is apparent, although Ribeiro (2000) specifies that while /ɨ/ and /ʌ/ have [RTR] and [ATR] features, the two vowels do not correspond to one another in the ATR harmony system he describes.

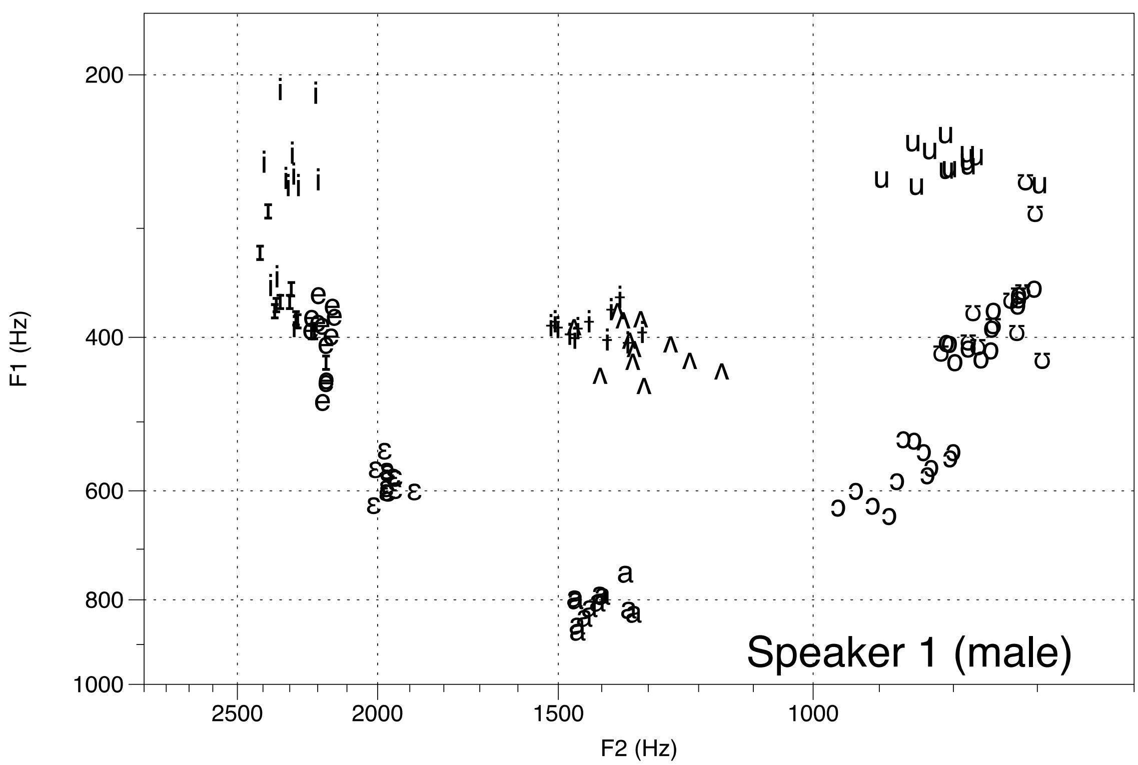

Figure 1. Formant plot of Speaker 1

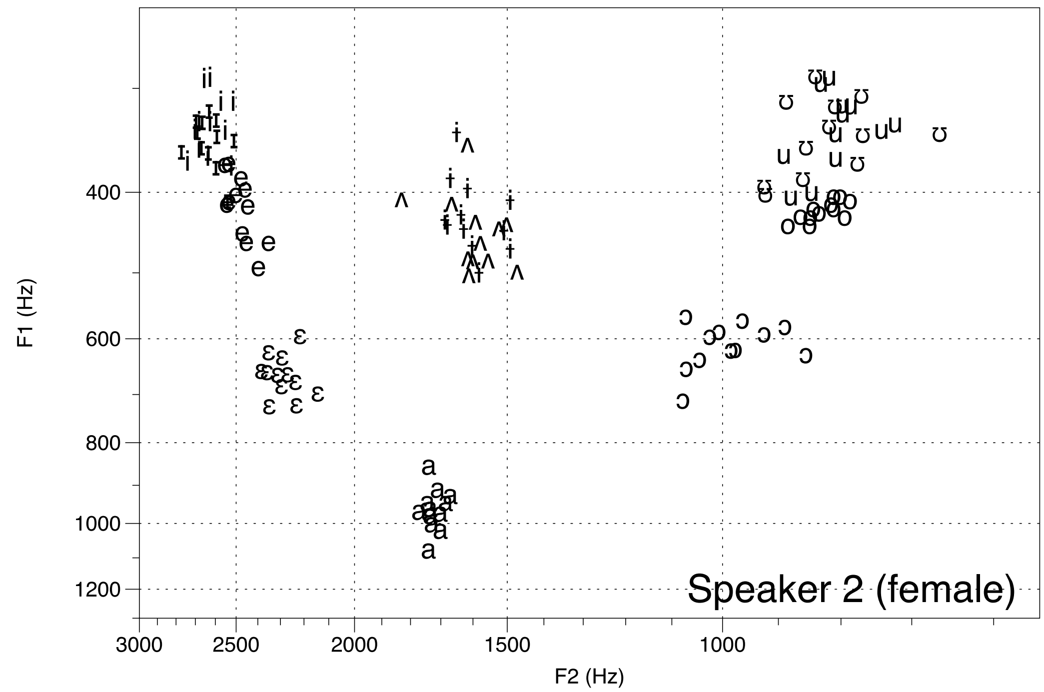

Figure 2. Formant plot of Speaker 2

<u>Frequency of the First and Second Formants</u>

In this section the results of statistical tests to determine whether vowel pairs differ in F1 and F2 values are presented. The values for F1 and F2 for each vowel were submitted to a *t*-test with a significance threshold of 0.05 for each speaker. Following this, a paired *t*-test was performed including data from both speakers to determine the overall relationship between vowel pairs. The results of these statistical tests are summarized in Tables 4 and 5.

Table 4. F_1 Difference Across [ATR]/[RTR] Vowel Pairs

Hypothesis	Speaker 1	Speaker 2	Overall
F_1 (e) < F_1 (ɛ)	$p \leq 0.0001$*	$p \leq 0.0001$*	$p \leq 0.0001$*
F_1 (i) < F_1 (ɪ)	$p \leq 0.0001$*	$p > 0.05$	$p \leq 0.0001$*
F_1 (o) < F_1 (ɔ)	$p \leq 0.0001$*	$p \leq 0.0001$*	$p \leq 0.0001$*
F_1 (u) < F_1 (ʊ)	$p \leq 0.0001$*	$p > 0.05$	$p \leq 0.0001$*

Note. *Significant

Table 5. F_2 Difference Across [ATR]/[RTR] Vowel Pairs.

Hypothesis	Speaker 1	Speaker 2	Overall
F_2 (e) > F_2 (ɛ)	p≤0.0001*	p≤0.0001*	p≤0.0001*
F_2 (i) > F_2 (ɪ)	p>0.05	p>0.05	p>0.05
F_2 (o) < F_2 (ɔ)	p≤0.0001*	p≤0.0001*	p≤0.0001*
F_2 (u) < F_2 (ʊ)	p=0.002	p>0.05	p>0.05

Note. *Significant

The F_1 null hypothesis (F_1 [ATR]= F_1 [RTR]) must be accepted in the case of Speaker 2's high vowel pairs, but is rejected elsewhere. That is, while the female speaker did not show a significant lowering of F_1 in the pairs of high vowels, the F_1 values differed significantly in every other intra-speaker vowel pair, as well in all vowels— including the high vowels— across speakers. The F_2 null hypothesis (F_2 [ATR]= F_2 [RTR]) must be accepted for both high vowel pairs (though Speaker 1 did show a significant difference between /u/ and /ʊ/, the variation was insignificant overall), but is rejected elsewhere. Unlike the lowering of F_1 across all vowels, F_2 varies disordinally, with the [ATR] back vowels having generally lower F_2 values, and the [ATR] front vowels having generally higher F_2 values.

While Speaker 1 distinguishes each pair of vowels in at least one dimension (i.e. F_1), both of Speaker 2's high vowel pairs are not significantly distinguished by the frequency of the first or second formant. This general overlap can be seen in Figure 2.

Based on the clustering of /ɨ/ and /ʌ/ as seen in Figures 1 and 2, a two-sample equal *t*-test was performed for both formants of these vowels, and found that neither speaker produces a significant difference distinguishing these vowels in either formant, and a cross-speaker paired *t*-test also found no significant difference overall (F_1: p=0.8, F_2: p=0.21).

Normalized Relative Formant Amplitude

In this section the normalized relative amplitude of the first to second formant (normalized A_1-A_2) for each vowel pair is considered. Figures 3 and 4 display the mean normalized A_1-A_2 values for each vowel and each speaker. The normalized A_1-A_2 values for each vowel pair were submitted to a two-sample equal *t*-test with a significance threshold of 0.05 for each speaker. Following this, a paired *t*-test was performed including data from both speakers to determine the cross-speaker relationship between vowel pairs.

Generally, the normalized A_1-A_2 value is higher for [ATR] than [RTR] vowels. This is an indication that [RTR] vowels have a higher degree of spectral flatness than their more sloped [ATR] counterparts. While the overall effect across both speakers and all vowel qualities is significant (p<.001), the null hypothesis (A_1-A_2 [ATR]= A_1-A_2 [RTR]) must be accepted in the case of the /i,ɪ/ and /o,ɔ/ vowel pairs, i.e. these vowel pairs are not shown to be statistically distinct on the basis of spectral slope. Other studies showing significant differences in this measure have similarly found that some vowel pairs do not participate to the same degree (Fulop et al. 1997, Guion et al. 2004). The cross-speaker significance of normalized A_1-A_2 values by vowel pair is displayed in Table 6.

Once again based on the clustering of /ɨ/ and /ʌ/, as well the insignificant variance between the F_1 and F_2 values across these two vowels, a two-sample equal *t*-test was performed comparing the normalized A_1-A_2 values of /ɨ/ and /ʌ/ for each speaker, and found that neither speaker produces a significant difference distinguishing these vowels through normalized A_1-A_2, and a cross-speaker paired *t*-test also found no significant difference overall (p=0.5).

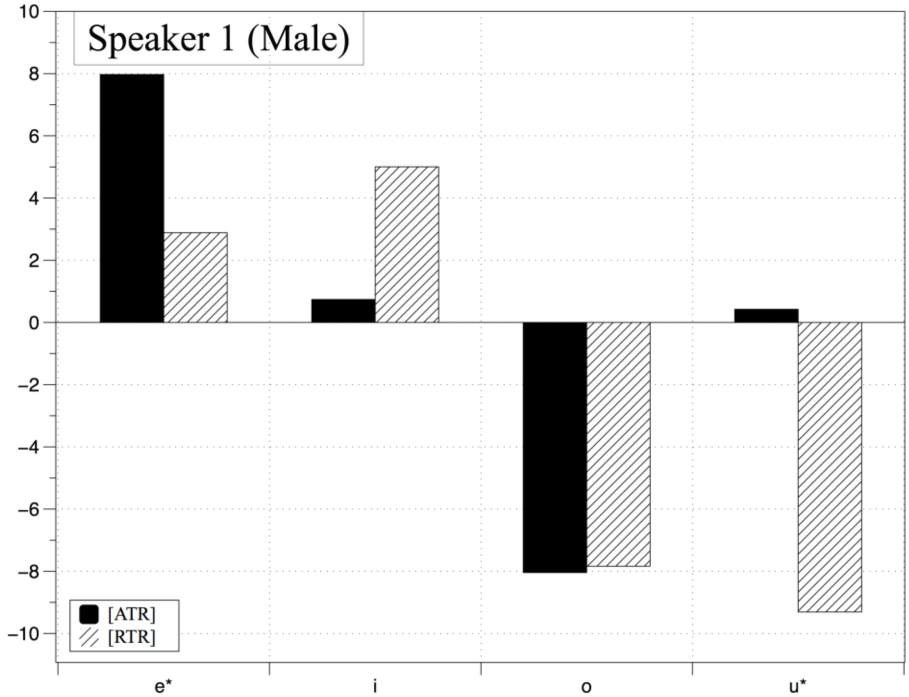

Figure 3. Normalized A_1-A_2 values (in dB) for Speaker 1

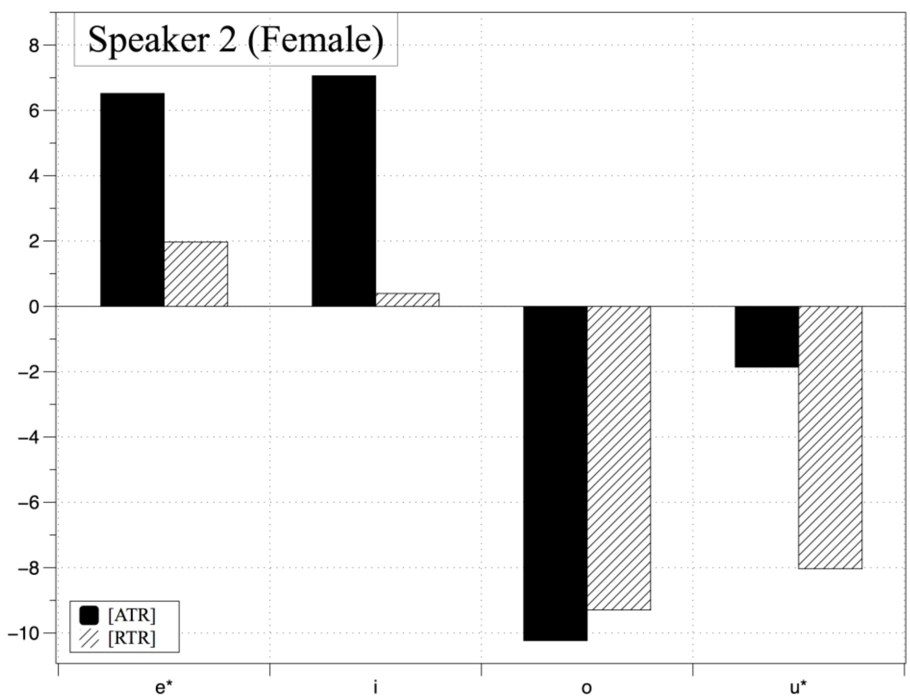

Figure 4. Normalized A_1-A_2 values (in dB) for Speaker 1

Table 6. A1-A2 Differences Across [ATR]/[RTR] Vowel Pairs

Hypothesis	Male	Female	Overall
A_1-A_2 (e) > A_1-A_2 (ɛ)	$p \leq 0.0001$*	$p=0.005$*	$p \leq 0.0001$*
A_1-A_2 (i) > A_1-A_2 (ɪ)	$p>0.05$	$p>0.05$	$p>0.05$
A_1-A_2 (o) < A_1-A_2 (ɔ)	$p>0.05$	$p>0.05$	$p>0.05$
A_1-A_2 (u) < A_1-A_2 (ʊ)	$p \leq 0.0001$*	$p=0.035$*	$p=.001$*

Note. *Significant

CHAPTER 5: SUMMARY AND DISCUSSION

The acoustic effects of the [ATR]/[RTR] distinction in Karajá are on the whole consistent with similar findings in both West African languages and those of Northeast Asia (e.g. Fulop et al. 1997 for Degema, Gulon et al. 2004 for Maa, Aralova et al. 2011 for Ewen, and Kang & Ko 2012 for Western Buriat and Tsongol). Table 7 summarizes the overall effects of the purported ATR distinction in Karajá.

Table 7. Summary of the Present Findings Regarding the Acoustic Correlates of ATR in Karajá

Measure	Findings
F_1	[ATR]<[RTR]
F_2	[ATR]<[RTR] for e/ɛ, [ATR]>[RTR] for o/c
Normalized A_1-A_2	[ATR]>[RTR] for e/ɛ and u/ʊ

First, the fundamental frequency of the first formant is consistently lower across all vowel pairs in Karajá, though Speaker 2's high vowel pairs are not significantly differentiated along F_1. This difference in F_1 is attributable to the increase back cavity size caused by pharyngeal expansion in the articulation of [ATR] vowels. Second, F_2 shows a disordinal effect across the vowels pairs wherein there is a significant effect on F_2 values. Specifically, the [ATR] mid vowels of Karajá are significantly more peripheral than their [RTR] counterparts, though no significant effect is seen among the high vowel pairs generally, though Speaker 1's /u, ʊ/ pair demonstrates a significant difference inline with the disordinal relationship of the mid vowel pairs. This is consistent with previously published observations that while F_2 may vary with the [ATR] feature, the nature and direction of this variability are not consistent cross-linguistically (e.g. Gulon et all 2004).

Finally, [ATR] vowels have generally higher normalized A_1-A_2 values than their [RTR] counterparts, thus demonstrating that [ATR] vowels have relative more energy in the lower formants than [RTR] vowels. One possible explanation for this effect is the muscular tension involved in the articulation of [ATR] vowels may create less damping of the lower frequencies. Further, the air viscosity in the pharyngeal constriction of [RTR] vowels may create greater damping in these low frequencies.

While each of the [ATR]/[RTR] vowel pairs differ generally in at least one of the above parameters, the vowels /ɨ/ and /ʌ/ show no significant differences in any acoustic measure in either speaker. In Ribeiro's analysis of the Karajá vowel system, /ʌ/ is an [ATR] vowel and /ɨ/ is a [RTR] vowel that does not alternate with /ʌ/, but rather seems impressionistically 'heavier' in [ATR] contexts. In the data analyzed in the present study, /ɨ/ and /ʌ/ do not seem to differ from one another at all in any of the three established acoustic correlates of ATR contrasts. It may be possible that the two speakers of Karajá in this study represent a merger of the non-low central vowels, thus leaving Karajá with one central vowels opaque to the process of ATR harmony (/a/) and one central vowel transparent to it (/ʌ/).

CHAPTER 6: REVIEW

Karajá stands as the unique American language claimed to incorporate the feature [ATR] in a system of vowel harmony. The acoustic characteristics shown to be correlated with the ATR systems of other languages correlate with the proposed ATR system of Karajá as well. The value of F_1 was shown to be lower in [ATR] than [RTR] vowels, consistent with the prediction based on a larger back cavity volume created by pharyngeal expansion. The value of F_2 was shown to vary disordinally among the mid-vowel pairs of Karajá, with [ATR] vowels being more peripheral than their [RTR] counterparts. The spectral slope of [ATR] vowels was to be generally greater than that of [RTR] vowels using the normalized relative formant amplitude calculated following Fulop et al (1998). Finally, the vowels /ɨ/ and /ʌ/ do not seem to vary significantly in any of the three acoustic measures considered in this study.

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APPENDIX: A_1-A_2 PRAAT SCRIPT

The following is the complete version of the Praat script used to implement the normalized A_1-A_2 calculations described in Fulop, et al. (1997) by Mills (2009). Much of this script includes Mills' implementation of an octave scaled version of these calculations, and these were not utilized in the development of this thesis. The entire script as written by Mills is presented here in interest of completeness.

```
### a1-a2measure.praat
# version 0.0.4
#
# copyright 2009 Timothy Mills
#
# This script is designed to measure spectral tilt following the technique
# described by Fulop, Kari, and Ladefoged (1998):
#
# Fulop, Sean A., Ethelbert Kari, and Peter Ladefoged.  1998.  An acoustic
#          study of the tongue root contrast in Degema vowels.  Phonetica 55:
#          80-98.
#
# In this method, the difference between the peak amplitude of the first
# formant (A1) and that of the second formant (A2) is compared to an
# acoustic model based on equations from Fant (Acoustic Theory of Speech
# Production, 1960).
#
#
# This script is designed to work as a subscript of the master script
# "spectralTiltMaster.praat", which can be obtained from the author:
#
#          Timothy Mills <mills.timothy@gmail.com>
#
# This script is released under the GNU General Public License version 3.0
# The included file "gpl-3.0.txt" or the URL "http://www.gnu.org/licenses/gpl.html"
# contains the full text of the license.

form Parameters for spectral tilt measure following Fulop et al
 comment TextGrid interval to measure.  If numeric, check the box.
 natural tier 2
 integer interval_number 0
 text interval_label v1
 comment Window parameters
 real windowPosition 0.5
 positive windowLength 0.032
 comment Output
 boolean output_to_matrix 1
```

```
 comment Do you want to save the visual record as an eps file?
 boolean saveAsEPS 1
 sentence inputdir /home/username/data/
 comment Manually check token?
 boolean manualCheck 1
 comment Analysis parameters
 positive maxFormantHz 5500
 positive preEmphFrom 50
 positive F1bandwidth 30
 positive F2bandwidth 80
 positive F3bandwidth 150
 positive spectrogramWindow 0.005
endform

###
### First, check that proper objects are present and selected.
###
numSelectedSound = numberOfSelected("Sound")
numSelectedTextGrid = numberOfSelected("TextGrid")
numSelectedFormant = numberOfSelected("Formant")
if (numSelectedSound<>1 or numSelectedTextGrid<>1 or numSelectedFormant<>1)
 exit Select only one Sound, one TextGrid, and one Formant object.
endif
name$ = selected$("Sound")
soundID = selected("Sound")
textGridID = selected("TextGrid")
formantID = selected("Formant")
###
### (end object check)

###
### Second, establish time domain.
###
select textGridID
if ‘interval_number’ > 0
 intervalOfInterest = interval_number
else
 numIntervals = Get number of intervals... ‘tier’
 for currentInterval from 1 to ‘numIntervals’
  currentIntervalLabel$ = Get label of interval... ‘tier’ ‘currentInterval’
  if currentIntervalLabel$==interval_label$
   intervalOfInterest = currentInterval
  endif
 endfor
endif

startTime = Get starting point... ‘tier’ ‘intervalOfInterest’
endTime = Get end point... ‘tier’ ‘intervalOfInterest’
midpoint = startTime + ((endTime - startTime) * windowPosition)
windowStart = midpoint - (‘windowLength’ / 2)
```

```
windowEnd = midpoint + (‘windowLength’ / 2)
### (end time domain check)

## Start loop (exit when user says it’s okay, or on first round if no user check)
#
checked = 1

repeat

 # Generate LPC, spectrum, and LTAS objects
 select ‘soundID’
 Extract part... ‘windowStart’ ‘windowEnd’ Gaussian1 1 yes
 soundPartID = selected("Sound")
 To Spectrum... yes
 spectrumID = selected("Spectrum")
 To Ltas (1-to-1)
 ltasID = selected("Ltas")

 select ‘formantID’
 f1Hz = Get mean... 1 ‘windowStart’ ‘windowEnd’ Hertz
 f2Hz = Get mean... 2 ‘windowStart’ ‘windowEnd’ Hertz
 f3Hz = Get mean... 3 ‘windowStart’ ‘windowEnd’ Hertz

 # Identify formant amplitudes A1, A2, A3
 #
 # Start by identifying ranges to look in for maximum LTAS energy - the
 # algorithm looks for the local maximum within ten percent above or below
 # the formant’s average frequency.  This script collects values for A1,
 # A2, and A3, following Bert Remijsen’s script, though A3 is not used in
 # the Fulop-Kari-Ladefoged technique.
 #
 searchRangeA1 = ‘f1Hz’ * 0.15
 searchRangeA2 = ‘f2Hz’ * 0.1
 searchRangeA3 = ‘f3Hz’ * 0.1
 lowerboundA1 = ‘f1Hz’ - ‘searchRangeA1’
 upperboundA1 = ‘f1Hz’ + ‘searchRangeA1’
 lowerboundA2 = ‘f2Hz’ - ‘searchRangeA2’
 upperboundA2 = ‘f2Hz’ + ‘searchRangeA2’
 lowerboundA3 = ‘f3Hz’ - ‘searchRangeA3’
 upperboundA3 = ‘f3Hz’ + ‘searchRangeA3’
 # Then query LTAS object to get the formant amplitudes.
 # Also, record the frequency of the amplitude peak.  If this is far from the
 # recorded formant frequency (f1Hz etc), there may be a problem.  The most
 # likely cause of such a discrepancy would be a non-stationary formant,
 # which violates one of the assumptions underpinning this measure.
 select ‘ltasID’
 a1dB = Get maximum... ‘lowerboundA1’ ‘upperboundA1’ None
 a1Hz = Get frequency of maximum... ‘lowerboundA1’ ‘upperboundA1’ None
 a2dB = Get maximum... ‘lowerboundA2’ ‘upperboundA2’ None
 a2Hz = Get frequency of maximum... ‘lowerboundA2’ ‘upperboundA2’ None
```

```
a3dB = Get maximum... 'lowerboundA3' 'upperboundA3' None
a3Hz = Get frequency of maximum... 'lowerboundA3' 'upperboundA3' None

# Model A1 and A2, calculate normalized A1-A2.
#
# These are the formulas from Fulop, Kari, and Ladefoged (1998).
# Note however the formula for glottal source and radiation characteristics
# (a1modelOther, a2modelOther) - I have omitted the negative sign before
# the "20" (which seems to have been a misprint).  The parameter 'g' is set
# to 1.0 for all measurements, but is included for formal completeness.
#
g = 1.0
a1modelF1 = g * 20 * log10((f1Hz^2 + (f1bandwidth/2)^2) / (sqrt((f1Hz - f1Hz)^2 +
(f1bandwidth/2)^2) * sqrt((f1Hz + f1Hz)^2 + (f1bandwidth/2)^2)))
a1modelF2 = g * 20 * log10((f2Hz^2 + (f2bandwidth/2)^2) / (sqrt((f1Hz - f2Hz)^2 +
(f2bandwidth/2)^2) * sqrt((f1Hz + f2Hz)^2 + (f2bandwidth/2)^2)))
a1modelF3 = g * 20 * log10((f3Hz^2 + (f3bandwidth/2)^2) / (sqrt((f1Hz - f3Hz)^2 +
(f3bandwidth/2)^2) * sqrt((f1Hz + f3Hz)^2 + (f3bandwidth/2)^2)))
a1modelFplus = 0.72 * (f1Hz/492)^2 + 0.0033 * (f1Hz/492)^2
a1modelOther = 20 * log10(2*((f1Hz/100)/(1+(f1Hz/100)^2)))
a1model = a1modelF1 + a1modelF2 + a1modelF3 + a1modelFplus + a1modelOther
a2modelF1 = g * 20 * log10((f1Hz^2 + (f1bandwidth/2)^2) / (sqrt((f2Hz - f1Hz)^2 +
(f1bandwidth/2)^2) * sqrt((f2Hz + f1Hz)^2 + (f1bandwidth/2)^2)))
a2modelF2 = g * 20 * log10((f2Hz^2 + (f2bandwidth/2)^2) / (sqrt((f2Hz - f2Hz)^2 +
(f2bandwidth/2)^2) * sqrt((f2Hz + f2Hz)^2 + (f2bandwidth/2)^2)))
a2modelF3 = g * 20 * log10((f3Hz^2 + (f3bandwidth/2)^2) / (sqrt((f2Hz - f3Hz)^2 +
(f3bandwidth/2)^2) * sqrt((f2Hz + f3Hz)^2 + (f3bandwidth/2)^2)))
a2modelFplus = 0.72 * (f2Hz/492)^2 + 0.0033 * (f2Hz/492)^2
a2modelOther = 20 * log10(2*((f2Hz/100)/(1+(f2Hz/100)^2)))
a2model = a2modelF1 + a2modelF2 + a2modelF3 + a2modelFplus + a2modelOther

a1a2model = a1model - a2model
a1a2measured = a1dB - a2dB
a1a2normalized = a1a2measured - a1a2model

a1offset = 'a1Hz' - 'f1Hz'
a2offset = 'a2Hz' - 'f2Hz'
a3offset = 'a3Hz' - 'f3Hz'

# Also, calculate octave-scaled version of spectral tilt (my own refinement
# on FKL):

f1octave = ln(f1Hz/100)/ln(2)
f2octave = ln(f2Hz/100)/ln(2)
fDiffOctave = f2octave - f1octave
octaveScaledST = a1a2normalized / fDiffOctave

# Now we need to report these measurements and record them for later
# display.
```

```
if (manualCheck or saveAsEPS)

 # Generate rounded versions of key measures
 specTiltDisp$ = fixed$(a1a2normalized,3)
 octaveScaledDisp$ = fixed$(octaveScaledST,3)
 f1disp$ = fixed$(f1Hz,3)
 f2disp$ = fixed$(f2Hz,3)
 f3disp$ = fixed$(f3Hz,3)
 a1disp$ = fixed$(a1dB,3)
 a2disp$ = fixed$(a2dB,3)
 a3disp$ = fixed$(a3dB,3)
 a1modDisp$ = fixed$(a1model,3)
 a2modDisp$ = fixed$(a2model,3)
 a1offsetDisp$ = fixed$(a1offset,3)
 a2offsetDisp$ = fixed$(a2offset,3)
 a3offsetDisp$ = fixed$(a3offset,3)

 # The following block creates a LTAS object with the modelled
 # amplitude spectrum for visual comparison with the measured
 # spectrum.
 #
 # Note the slightly cheeky use of the offset term to bring the
 # modelled graph up to the level of the actual graph.  This makes
 # visual comparison easier, without betraying the important
 # properties of the graph - the relative amplitudes of F1 and F2 in
 # the measured and modelled spectra.

 # The value "modelOffset" is used to shift the dB of the displayed tracks
 # so that the model and the real spectrum match at the F1 peak.  This
 # makes the plot easier to interpret with respect to the measure being
 # generated, and does not remove any important information.
 modelOffset = a1dB - a1model

 select ‘ltasID’
 Copy... model
 modelID = selected("Ltas", 1)
 Formula... modelOffset + 20 * log10((f1Hz^2 + (30/2)^2)/(sqrt((x - f1Hz)^2 + (30/2)^2) *
sqrt((x + f1Hz)^2 + (30/2)^2))) + 20 * log10((f2Hz^2 + (80/2)^2)/(sqrt((x - f2Hz)^2 + (80/2)^2) *
sqrt((x + f2Hz)^2 + (80/2)^2))) + 20 * log10((f3Hz^2 + (150/2)^2)/(sqrt((x - f3Hz)^2 +
(150/2)^2) * sqrt((x + f3Hz)^2 + (150/2)^2))) + 0.72 * (x/492)^2 + 0.0033 * (x/492)^2 + 20 *
log10(2*((x/100)/(1+(x/100)^2)))

 ###
 ### Display spectrogram and formant tracks in picture window
 ###

 Erase all

 maxFrequency = maxFormantHz
 select ‘soundID’
```

```
To Spectrogram... ‘spectrogramWindow’ ‘maxFrequency’ 0.002 20 Gaussian
spectrogramID = selected ("Spectrogram", 1)

# LTAS spectra, with marks for F1, F2, and F3
#
# Actual data is displayed in black.  The modelled smoothed (and offset)
# spectrum is displayed in red.

select ‘ltasID’
minDB = Get minimum... 0 ‘maxFormantHz’ None
maxDB = Get maximum... 0 ‘maxFormantHz’ None
dBrange = maxDB-minDB
maxDB = maxDB + 0.1*dBrange

Select outer viewport... 0 6 0 4

select ‘ltasID’
Draw... 0 ‘maxFrequency’ ‘minDB’ ‘maxDB’ yes curve
Red
select ‘modelID’
Draw... 0 ‘maxFrequency’ ‘minDB’ ‘maxDB’ yes curve

Green
circleRadius = maxFormantHz / 100

One mark top... ‘f1Hz’ no no yes F1
Draw circle... ‘a1Hz’ ‘a1dB’ ‘circleRadius’
a1dBlabel = a1dB + 0.05*dBrange
Text... ‘a1Hz’ Centre ‘a1dBlabel’ Half  A1

One mark top... ‘f2Hz’ no no yes F2
Draw circle... ‘a2Hz’ ‘a2dB’ ‘circleRadius’
a2dBlabel = a2dB + 0.05*dBrange
Text... ‘a2Hz’ Centre ‘a2dBlabel’ Half  A2

One mark top... ‘f3Hz’ no no yes F3
Draw circle... ‘a3Hz’ ‘a3dB’ ‘circleRadius’
a3dBlabel = a3dB + 0.05*dBrange
Text... ‘a3Hz’ Centre ‘a3dBlabel’ Half  A3

Black

# Object name at bottom
Select outer viewport... 2.5 3.5 4 4.5
Text... 0 Centre 0 Half  A1-A2

# Set selection to whole in case user wants to save display as sample
Select outer viewport... 0 6 0 4.5

if saveAsEPS
```

```
  Write to EPS file... ‘inputdir$’’name$’.A1A2.eps
 endif

 if manualCheck
  beginPause ("Check results.")
   comment ("Hit <accept> to continue, or")
   comment ("<adjust> to remeasure current token.")
  clicked = endPause("Accept","Adjust",1)

  if ‘clicked’ = 1
   checked = 1
  else
   checked = 0

   ##
   # This is where the user adjust parameters in light
   # of a bad formant measure.  Ideally, these adjustments
   # would carry over to following tokens, but for that we
   # would have to restructure so that this pause form
   # happens in the master script.  This will do for now.
   #
   beginPause ("Adjust parameters")
    positive ("windowPosition", ‘windowPosition’)
    positive ("windowLength", ‘windowLength’)
    positive ("maxFormantHz", ‘maxFormantHz’)
    positive ("preEmphFrom", ‘preEmphFrom’)
    positive ("f1bandwidth", ‘f1bandwidth’)
    positive ("f2bandwidth", ‘f2bandwidth’)
    positive ("f3bandwidth", ‘f3bandwidth’)
    positive ("spectrogramWindow", ‘spectrogramWindow’)
   endPause ("Continue", 1)
   #
   ##
  endif
  # end if ‘clicked’

 endif
 # end if ‘manualCheck’

 # Clean up objects generated for analysis
 select ‘soundPartID’
 plus ‘spectrumID’
 plus ‘ltasID’
 plus ‘modelID’
 plus ‘spectrogramID’
 Remove

endif
# end if (manualCheck or saveAsEPS)
```

```
until checked = 1
#
## (end of repeat...until loop, where user accepts output of measure)

# Record relevant measures in a Matrix object (if requested) to be passed
# back to the master script.

if output_to_matrix
 Create simple Matrix... FulopEtAlMeasures 1 11  0
 Set value... 1 1 ‘a1a2normalized’
 Set value... 1 2 ‘octaveScaledST’
 Set value... 1 3 ‘a1dB’
 Set value... 1 4 ‘a2dB’
 Set value... 1 5 ‘a3dB’
 Set value... 1 6 ‘a1Hz’
 Set value... 1 7 ‘a2Hz’
 Set value... 1 8 ‘a3Hz’
 Set value... 1 9 ‘a1offset’
 Set value... 1 10 ‘a2offset’
 Set value... 1 11 ‘a3offset’
else
 select ‘soundID’
 plus ‘textGridID’
 plus ‘formantID’
endif
```