The Phonetics of Register in Takhian Thong Chong

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Abstract

The language Chong uses a combination of different acoustic correlates to distinguish among its four contrastive phonation types (registers). Electroglottographic and acoustic data were examined from original fieldwork on the Takhian Thong dialect. EGG data shows high open quotient (OQ) values for the breathy-modal register, low OQ values for the modal-tense register, intermediate OQ values for the modal register, and rapidly changing high to low OQ values for the breathy-tense register. Acoustic correlates indicate that H1-A3 and H1-A2 best distinguish between breathy and non-breathy phonation types, but measures like H1-H2 and pitch are necessary to discriminate between tense and non-tense phonation types. A comparison of spectral tilt and OQ measures shows the greatest correlation between OQ and H1-H2, suggesting that changes in the relative amplitude of formants are not directly related to changes in the open period of the glottal cycle. OQ is best correlated with changes in the degree of glottal tension.

1 Introduction

Chong is an Austroasiatic language (Mon-Khmer: Pearic) spoken in Chanthaburi province, Thailand and in northwestern Cambodia (Choosri 2002). This study investigates the phonetics of register in the dialect of Chong spoken in the Takhian Thong community. The term *register* is used in the Southeast Asian linguistic literature with reference to a collection of contrastive suprasegmental properties like phonation type, pitch, vowel quality, intensity and vowel duration (Henderson 1952, 1985). A register language is distinct from a tone language because contrastive phonation type typifies the former while the contrastive pitch typifies the latter. Phonation type is to a register language what tones are to a tone language.

Most register languages contrast only two phonation types, e.g. Middle-Khmer (Jacob 1968) and Wa (Watkins 2002). Those which contrast three are quite rare, but do exist, e.g. Jalapa Mazatec (Kirk, Ladefoged & Ladefoged 1993) and Bai (Edmondson and Esling 2006), and, of course, languages with a 4-way phonation-type contrast are extremely rare. Only two languages in the world have been found to use this number of contrasts: Chong (Thongkum 1991) and !Xóõ (Traill 1985). Chong contains both dynamic (contour) and level registers. There is a modal register, a modal-tense register, a breathy-modal register, and a breathy-tense register. While the temporal dynamics of pitch is considered significant in the production and perception of tone (Bao 1999, Gordon 2001, Avelino 2003, Liu & Samuel 2004, Khouw & Ciocca 2007, etc.), there are very few studies that have focused on the temporal dynamics of phonation type with respect to register.[1] This is understandable as both tone and tonal contours are much more common in languages of the world than register and register contours are. However, the existence of such patterns necessitates a phonetic analysis of how they are produced for both research in phonetic typology and research investigating

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[1] Thongkum 1988 (on Chong) and Esposito 2004 (on Zapotec) are notable exceptions.

the acoustic and articulatory manifestation of distinct glottal states. The notion of a tonal contour is well-known to most phonologists, where a single prosodic unit may have two or more suprasegmental specifications given an autosegmental representation (Goldsmith 1976). However, the presence of phonation-type contours implies that multiple laryngeal specifications may be present on a single prosodic unit. Phonation may behave prosodically like tone in its representation in the phonology of a language.

Apart from describing the phonetics of a typologically rare contrast, this study investigates changes in phonation type along the duration of Chong vowels contrasting the different registers. Both electroglottographic (EGG) and acoustic recordings were used to analyze the differences among the registers. A number of spectral tilt measures and F0 were compared using linear discriminant analysis (LDA). These measures are compared to the articulatory data from the EGG signal. The results suggest that changes in H1-H2 are correlated more closely with changes in open quotient (OQ) derived from the EGG signal than mid-band spectral slope measures like H1-A2 and H1-A3 are. While a number of parameters are predicted to significantly contrast the four registers, H1-A3 and H1-A2 significantly distinguishes the breathy registers from the non-breathy ones while H1-H2 significantly distinguishes registers with increased glottal tension from those lacking it.

2 Background

2.1 Chong Segmental Phonology

There are three major dialects of Chong: Northern Khao Khitchakut, Pong Nam Ron, and Southern Khao Khitchakut (Choosri 2002). Takhian Thong Chong, the focus of the paper, belongs to the Northern Khao Khitchakut dialect region. Like the other Chong dialects, Takhian Thong Chong phonology is noteworthy for having a four-way contrast among place of articulation in stops, a complex vowel inventory, and a four-way contrast in register. The consonant inventory is given in Table (1) and the vowel inventory in Table (2).

Table 1: Takhian Thong Chong Consonant Inventory

	Bilabial	Alveolar	Palatal	Velar	Glottal
Stops	p p^h	t t^h	c, cɕ	k k^h	ʔ
Fricatives		s			h
Trills		r			
Nasals	m	n	ɲ	ŋ	
Laterals		l			
Approximants	w		j		

Table 2: Takhian Thong Chong Vowel Inventory

	Front	Central	Back	
			Unrounded	Rounded
Close	i, ii			u, uu
Close-Mid	e, ee	ə	ɤ, ɤɤ	o, oo
Mid-Open	ɛ, ɛe			ɔ, ɔɔ
Open		a, aa		
Diphthongs	iə, iu	aɪ, ao	ɤə	uə

All consonant phonemes given in Table (1) may occur as the onset of a syllable with any of the vowels. Most of these same consonants can occur as codas, with the exception of the aspirated stops, /s/, and /r/. Glottal consonants /h/ and /ʔ/ may also occur as coda consonants, but only on modal and breathy-modal registers. All registers may occur on closed syllables containing both long and short vowels, with sonorant or stop codas. I show this in Table (3), but I was unable to elicit CVN (short vowel + sonorant coda) forms for the breathy-modal register during fieldwork. Only the modal and breathy register may occur on open syllables. For instance, the word /tṳṳ/ *to escape* is breathy while the word /hɔɔ/ *dinner, food* is modal.

Aspirated stops have a restricted distribution in Takhian Thong Chong. They occur only as the onsets of modal vowels, e.g. /tʰoh/ *breast* and /pʰat/ *tail.* This is different than the nearby dialect of Khlong Phlu Chong which maintains the aspiration distinction on all registers, but similar to the Wang Kraphrae dialect which has lost many of the aspirated stops in these environments (Ungsitipoorporn 2001).[2] It is possible that the lost aspirated stops have conditioned or merged with the register on the following vowel. The pattern whereby aspiration conditions register is called *registrogenesis* and has been described for many languages in the Mon-Khmer family (Haudricourt 1954, Ferlus 1979, Wayland & Jongman 2002). However, it is an open question as to whether this has also occurred in Chong.

There is an effect of register on vowel quality in Chong. This is most noticeable on the non-closed vowels. In general, vowels occurring on the breathy or breathy-tense register are higher than those occurring on the modal or modal-tense register. The open-mid vowels (/ɛ/, /ɛɛ/, /ɔ/, or /ɔɔ/) never occur on each of these registers. Furthermore, the vowel /a/ is realized with a slightly higher variant when it occurs on the breathy or breathy-tense register. Thongkum (1991) found a similar effect measuring vowels on different registers. This effect is most noticeable on words with a long vowel in the breathy-tense register because the vowel quality as well as the voice quality changes throughout the course of the vowel. So, a word like /pa̤a̰j/ “two" is realized as [pʌ̤a̰j] where the initial duration of the long vowel is more closed. The correlation between breathiness and vowel-raising has been mentioned in the previous literature on Chong (Ungsitipoorporn 2001) and is a well-established phenomena within Mon-Khmer languages as a source of sound change (Ferlus 1979).

2.2 Chong Register

The register contrast in Takhian Thong Chong includes a modal register, a modal-tense register, a breathy-modal register, and a breathy-tense register. The hyphen here indicates that there is a movement from one phonation type to another over the vowel's duration. Thus, the breathy-tense register consists of breathy voice following the release of the onset consonant, with a change in voice quality towards more tense or pressed phonation. This description of the Chong register system follows that of Thongkum (1988), though I think that *tense* is a better term to use than *creaky* as it more accurately describes the phonation-type found in Takhian Thong Chong. Examples of each register are given in table (3).

2.3 Phonation Type

2.3.1 Production Aspects

While there are a number of possible laryngeal configurations, linguistically-constrastive phonation types fall within relatively few categories : creaky voice, tense voice, modal voice, lax voice, and breathy voice. These distinct phonation types lie along a continuum that is defined in terms of the aperture between the arytenoid cartilages where creak has the least aperture and breathiness the greatest (Ladefoged 1971, Gordon & Ladefoged 2001). While the aperture between the vocal folds is an important articulatory parameter, laryngeal tension and aerodynamic conditions are also relevant to the characterization of phonation type. We may define each phonation type with these parameters.

Modal phonation is characterized by neither broadband spectral energy in the upper harmonics nor irregular vocal fold vibration where the arytenoid cartilages are neither pulled apart nor pushed together (Ní Chasaide & Gobl, 1997, Ladefoged & Maddieson, 1996). During the production of modal phonation, there

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[2] Aspirated palatal stops occur before all registers and are an apparent exception to this pattern.

Table 3: Takhian Thong Chong Registers

Word	*Register*	*Gloss*	*Syllable Structure*
lɔɔŋ	modal	‘stride’	CVVN
ceet	modal	‘to sharpen wood’	CVVT
tɔŋ	modal	‘house’	CVN
p^{h}at	modal	‘tail’	CVT
lɔ̰ɔ̰n	modal-tense	‘navel’	CVVN
cḛḛt	modal-tense	‘deer’	CVVT
pa̰j	modal-tense	‘palm’	CVN
cɕo̰k	modal-tense	‘pig’	CVT
ra̤a̤j	breathy-modal	‘ten’	CVVN
pa̤a̤t	breathy-modal	‘peel’	CVVT
pə̤t	breathy-modal	‘to fan’	CVT
pa̤a̰j	breathy-tense	‘two’	CVVN
cɕɔ̤ɔ̰ŋ	breathy-tense	‘Chong’	CVVN
kəta̤a̰k	breathy-tense	‘bean’	CVVT
tṳŋ	breathy-tense	‘squash’	CVN
p^{h}ɣ̤t	breathy-tense	‘rattan’	CVT

is moderate adductive tension and medial compression of the vocal folds (Laver, 1979). There is adequate subglottal pressure present to overcome vocal fold impedance. As a result, sustained voicing with regular periodicity characterizes this phonation type.

Both lax and breathy phonation involve an increase in the aperture between the vocal folds, such that the posterior portion to the midline of one vocal fold never comes in contact with the other fold (Laver 1979, Pennington 2005). The vocal folds have minimal adductive tension, weak medial compression, and little longitudinal tension (ibid). The required transglottal pressure differential is allowably smaller since the vocal folds have less impedance. Because of this and the increased aperture, the glottal wave is more sinusoidal for both these phonation types. What distinguishes lax from breathy phonation though is the *degree* of vocal fold tension and the amount of aperiodic noise that dominates the upper spectrum. Breathy phonation contains substantial broadband spectral energy that arises due to greater vocal fold aperture. Lax phonation does not contain substantial high amplitude noise components (Pennington 2005).

Creaky and tense phonation are similar in that both involve decreased aperture between the vocal folds. The vocal folds are mostly closed for this phonation type, vibrating mainly at the ligamental portion between the arytenoids. Both phonation types are characterized with increased adductive tension and medial compression (Ní Chasaide & Gobl, 1997). However, while tense phonation is characterized with mostly periodic vocal fold vibration, creaky phonation contains substantial frequency modulation (jitter) and amplitude modulation (shimmer) (Pennington 2005). The cause of this may arise from the adduction of the ventricular folds during the production of creaky phonation. Adduction of the false vocal folds produces contact between their inferior surfaces and the superior surfaces of the true vocal folds. This would result in a compressed and thick structure that would inhibit voicing (Laver, 1979). While ventricular fold bracing may be more common with creaky phonation than with tense phonation, Edmondson & Esling (2006) and Tumtavitikul (2005) found that the ventricular folds are also used during the production of tense voice. Aerodynamically, conditions for sustained voicing are similar for both phonation types where the required transglottal pressure differential must be must be larger since the vocal folds have increased impedance. Similar to lax and breathy phonation type, tense and creaky phonation type may only differ in their degree of vocal fold tension and degree of modulation.

These articulatory descriptions of phonation type bear directly on the utility of articulatory measures like open quotient (OQ) or closed quotient (CQ) in distinguishing register in Chong. The open quotient is the percentage of the glottal period where the vocal folds are not in contact. This comprises the portion of the glottal wave between the abduction of the vocal folds at their upper margin until adduction occurs along their lower or central margins (Rothenberg 1981, Titze & Talkin 1981, Childers & Krishnamurthy 1985, Childers & Lee 1991, Michaud 2004). The CQ measure is simply derived from the OQ measure (1-OQ = CQ). Assuming that subglottal pressure remains constant, the impedance of the vocal folds is directly related to the closed quotient, where an increased impedance due to strong adductive tension and medial compression of the vocal folds leads to longer closed periods in the glottal cycle. The subglottal pressure must *build up* over a longer duration in these cases. Conversely, low impedance on glottal airflow due to weak adductive tension between the vocal folds will lead to shorter closed periods in the glottal cycle. In such cases, it is possible that low impedance may also prevent full closure from being reached during a glottal period. Accordingly, it is possible to use OQ as a measure of phonation type since it correlates with glottal tension.

2.3.2 Acoustic Measures

Apart from examining the glottal source directly, a number of acoustic measures are useful correlates of phonation type (Ladefoged, Maddieson, & Jackson 1988, Ní Chasaide & Gobl 1997, Pennington 2005, Kreiman, Gerratt, & Antoñanzas-Barroso 2007). An examination of power spectra often reveals differences between phonation types. The theory behind this method is that the increased closing velocity of the vocal folds that occurs with greater adductive tension (as found in tense or creaky phonation) causes an excitation of higher harmonics. Slower vocal fold closure which occurs with less adductive vocal fold tension (as found in breathy phonation) does not excite the upper harmonics and causes a lowering of the harmonics' amplitude (Ladefoged, Maddieson, and Jackson 1988, Ní Chasaide and Gobl 1997, Pennington 2005). Thus, one measures the amplitude of higher harmonics to see, albeit indirectly, how tense the vocal folds are during their vibration.

Spectral tilt measures can be divided into those which compare low-range, mid-range, and high-range regions of the spectrum. Low range measures like H1-H2 have a close correlation to OQ values and are therefore good measures of the degree of glottal tension present in different phonation types (Stevens & Hanson 1995, Holmberg et al. 1995, Sundberg et al. 1999). H1-H2 successfully distinguishes modal from breathy (and creaky) phonation in a variety of languages, e.g. !Xóõ (Traill & Jackson 1987), Gujarati (Fisher-Jørgensen 1967, Pennington 2005), Tsonga (Ladefoged & Antoñanzas-Barroso 1985), Wa (Watkins 2002), Jalapa Mazatec (Blankenship 2002, Pennington 2005), Chanthaburi Khmer (Wayland & Jongman 2003), and Fuzhou, Green Hmong, White Hmong, Santa Ana del Valle Zapotec, San Lucas Quiaviní Zapotec, and Tlacolula Zapotec (Esposito 2006). Ladefoged and Maddieson (1985) mention that H1-H2 values were greater for lax syllables[3] than for tense syllables in Jingpho, Hani, Yi, and Wa. Kreiman, Gerratt, & Antoñanzas-Barroso (2007) examined 78 different spectral measures of voice quality within a principal components analysis where the first factor accounting for the most variance between different glottal wave shapes corresponded to H1-H2. While substantial evidence supports the use of this measure in distinguishing certain phonation types, both Blankenship (2002) and Esposito (2006) report that it does not distinguish the breathy-modal from modal register in Chong, Mon, and Tamang (incidentally all Mon-Khmer languages). Blankenship (2002) examined the modal and breathy-modal registers in Chong with power spectra at 25 ms. intervals throughout the vowels. She found that H1-A2 is a more reliable indicator of the difference between these two registers than H1-H2. Contra Edmondson (1997), Blankenship (2002) also found that the breathy register has gradually increasing breathiness (and therefore should have *increasing* glottal airflow). These specific findings will be re-evaluated in light of the data in this paper.

Mid range measures of spectral tilt include H1-A1, H1-A2, H1-A3, and A1-A3. Each of these measures involve a calculation of the amplitude of the different formants, i.e. A1 = amplitude of F1, A2 = amplitude of F2, etc. Accordingly, changes in vowel quality will alter formant frequency. Since radiation impedance is approximately proportional to frequency, the wide-band spectral slope is approximately -6 dB/octave for modal phonation (Klatt 1980, Pennington 2005). Shifts in the center formant frequency due to vowel quality

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[3] The authors are specifically referring to a lax *laryngeal* setting here.

changes will affect these measures. So, given a vowel [i] with a high F2 frequency value and a vowel [u] with a low F2 frequency value, the H1-A2 calculation for these vowels will be substantially different even if phonation type parameters remain constant. This has caused some researchers to question the validity of using mid range measures of spectral tilt. However, such measures have been used to reliably distinguish phonation type in a variety of languages. Esposito (2006) shows that H1-A1, H1-A2, and H1-A3 distinguish breathy from modal phonation in a variety of languages including Chong, concluding that the most successful measure of spectral tilt is H1-A3. Blankenship (2002) found that H1-A2 and H1-A3 distinguished creaky and modal phonation type in Jalapa Mazatec but these same measures did poorly distinguishing breathy from modal voice. Yet, Traill & Jackson (1987) found that H1-A2 is a strong correlate that distinguishes the same phonation types in Tsonga. The acoustic importance of mid range spectral tilt measures seems to be dependent on both particular languages and particular phonation types.

Research on phonation type has also found that there is an interaction between the degree of glottal aperture and pitch (Hombert 1978, Ladefoged & Maddieson 1985, Thongkum 1988, Gordon and Ladefoged 2001). The claim of these authors is that increased glottal tension causes pitch raising while decreased glottal tension causes pitch lowering. It is possible that speakers who raise their larynx during the production of tense voice (see section (2.3.1)) may concomitantly trigger pitch raising as well. If this is true, then pitch-raising in tense phonation is best explained articulatorily. For breathy voice, the pitch effect is purely aerodynamic: increased glottal airflow lowers subglottal pressure which then lowers pitch (Hombert 1978). The connection between increased pitch and phonation type holds for previous studies of Chong. Thongkum (1988, 1991) finds that the modal-tense register has the highest F0 value, appearing with a rise-fall F0 contour in most cases, while the breathy register is realized with the lowest F0.

Apart from pitch and spectral tilt, researchers have also found that nonmodal phonation types often have longer duration than modally-phonated vowels in a variety of languages, but not universally (Gordon & Ladefoged 2001). Corresponding with this pattern are languages which only permit nonmodal phonation to occur on stressed syllables, as in Quileute (Powell & Woodruff 1976) and Coatzospan Mixtec (Gerfen 1999). Thongkum (1991) found that duration is not a strong correlate of the register contrast in Chong, with the exception of the breathy-tense register which is often shorter than the other registers. She finds no difference in vowel duration among the other registers.

Thongkum (1991) used H1-A1 as a measure of spectral tilt on the different registers. However, her measurements did not distinguish the registers because both the inconsistency in the position of F1 and the dynamic nature of the registers caused problems for the measure. Unfortunately, Thongkum only measured H1-A1 from one position on each vowel. Since Chong has register contours, spectral tilt measures at a single location on the vowel are not suitable for distinguishing the acoustic difference between the phonation types on each register. Rather, measures must be taken at several points across the duration of the vowel. This *dynamic* method for investigating phonation type is explicitly used in Edmondson's (1997) analysis of Chong. Edmondson briefly investigated glottal airflow throughout the duration of selected tokens of the different registers. He found that the breathy-modal and breathy-tense registers have high amplitude glottal airflow at the onset of the vowel while the modal-tense and breathy-tense registers have a marked low amplitude glottal airflow pulses during the second half of their duration, with some concomitant irregularity in the pulse amplitude. This suggests that the registers with breathiness have more airflow mainly during the beginning of the vowel while the tense registers have increased tension and lower airflow over the latter portion of the vowel. This finding agrees with the observation in Thongkum (1991) that glottal tension is timed toward the end of the vowel.

Both Blankenship (2002) and Edmondson (1997) used a dynamic measure over the duration of the vowels which allowed them to accurately distinguish between Chong registers using different acoustic measures. The present study also examines trajectories of acoustic measures of phonation type data over vowels produced in the four registers of Chong. In addition to spectral tilt measures, pitch, and duration[4] the study uses laryngographic data as a comparison to the acoustic measures of each register.

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[4] There are a number of other significant acoustic measures which may be used to distinguish phonation type, including jitter, shimmer, HNR (harmonic to noise ratio), H1 amplitude, high range spectral tilt measures, and aspiration noise (Pennington 2005). However, these particular measures were not used in this study.

3 Laryngographic Data

3.1 Method

Electroglottographic (EGG) data was acquired using a Laryngograph® model portable electroglottograph which was connected to one channel of an M-Audio® USB audio interface. A microphone was connected to another channel's input. The audio interface was connected to an Apple® iBook G3 computer where both channels were synchronously acquired using Praat 4.2 (Boersma & Weenink, 2007). Subjects were given all instructions in Thai with the help of an interpreter (S.N.). Either the interpreter or I gave the Thai word which was translated into Chong by the speakers.

EGG data from 7 speakers (4 female, 3 male), age 30-76, was elicited. Due to the loss of electrode-neck contact for many of their tokens, two speaker's data (1 female, 1 male) were not included in this investigation. In total, 39 words each repeated 5 times were elicited from each speaker. The word-list was designed to be balanced so that each register would appear in multiple syllable types on short and long vowels. Upon later investigation, some of the words that I elicited turned out to contain long vowels rather than short ones. As a result, there is a balanced list for all registers with long vowels followed a coda sonorant (N). Three words containing a long vowel and sonorant coda are analyzed for each register, with the modal register containing four such words. One word containing a long vowel and a stop coda for each register were analyzed as well. In sum, 13 words x 5 repetitions x 5 subjects = 330 tokens included in the analysis, shown in table (4).

Table 4: Words used in EGG analysis

Word	*Register*	*Gloss*	*Word*	*Register*	*Gloss*
tɔɔŋ	modal	*six*	ra̤a̤j	breathy-modal	*ten*
lɔɔŋ	modal	*stride*	lɔ̤ɔ̤ŋ	breathy-modal	*husband*
ceew	modal	*to go*	cṳṳn	breathy-modal	*to send*
ʔaaw	modal	*day*			
tɔ̰ɔ̰ŋ	modal-tense	*fear*	pa̤a̰j	breathy-tense	*two*
lɔ̰ɔ̰n	modal-tense	*navel*	cęɔ̤ɔ̰ŋ	breathy-tense	*Chong*
pḛḛw	modal-tense	*dinner*	ro̤o̰j	breathy-tense	*melon*

Electroglottography (EGG) involves the use of electrical current to determine the degree of abduction or adduction between the vocal folds. EGG peak maxima correspond to the moment of maximum contact between the vocal folds while peak minima correspond to the moment of minimum contact between the vocal folds (Childers & Krishnamurthy 1985, Childers & Lee 1991, Heinrich et al. 2004). Both the OQ and the CQ were extracted from the derivative of the EGG signal (DEGG). These measures require an accurate estimation of the moment of vocal fold separation. Since the EGG peaks do not correspond to the closing or opening instants of the vocal folds, the DEGG signal is used (Childers & Krishnamurthy 1985, Childers & Lee 1991, Heinrich et al. 2004, Michaud 2004). An EGG and its corresponding DEGG signal is shown in Figure 1.

The vowel portions within each EGG data file were segmented and labelled using Praat 4.6 (Boersma & Weenink 2007). The data was then analyzed using a peak detection script in Matlab (version 7.5). Within the script, the original 44.1 kHz EGG signal was band-pass filtered from 5-1200 Hz to eliminate low frequency DC components and any high frequency peaks unrelated to the opening or closing phases of vocal fold vibration. The signal was then smoothed with a third order Butterworth filter (-18 dB/octave) with a 0.054 normalized cutoff frequency. Peak maxima or minima that were less than 10% of the amplitude of the highest amplitude maxima or minima, respectively, were considered erroneous. Wherever the script detected two consecutive minima or maxima, the one with greater amplitude was chosen. The output file of the script provided the EGG signal maxima and minima, the DEGG maxima and minima, period durations, and CQ & OQ values calculated from the DEGG signal. The output files were then visually inspected for remaining erroneous peaks. If more than three OQ values showed a greater than 10% rise or fall from an

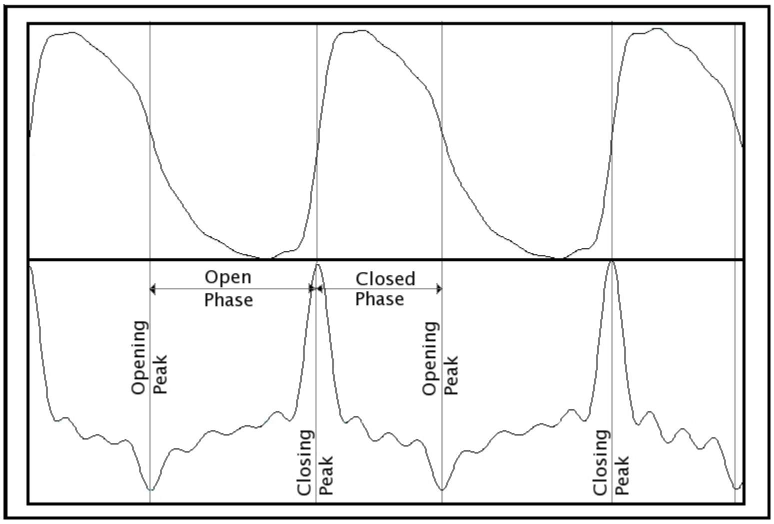

Figure 1: Example of Filtered EGG (top) and DEGG (bottom) signal

adjacent value, the token was omitted. If there were three or fewer erroneous OQ values, these data points were replaced with NA values. The output OQ data was then time-normalized using R (2007) to allow for a proportional comparison between the different speakers and tokens. OQ was averaged over 12 even intervals of the token's vowel.

3.2 Results

The results of the OQ measures are shown in Figure 2 along with 95% confidence intervals. Individual speakers' OQ data is given in Table 5. Confidence intervals are wider at time index 12 because the script was unable to calculate OQ accurately for some tokens, resulting in a smaller sample size. For all registers, there is a declination in OQ throughout the duration of the vowel, with the breathy-tense register showing the sharpest decline in OQ. The breathy-modal register shows the highest OQ value which gradually declines toward the endpoint of the vowel while the modal-tense register shows the lowest OQ value which similarly declines. The modal register does not show substantial declination in OQ, lying between the values for the breathy-modal register and the modal-tense register. At time index 1, the breathy-tense register shows overlap in OQ value with the breathy-modal register, but at time index 10-12, it shows overlap with the modal-tense register.

Results from a two-way ANOVA at each time index show a significant effect of register on OQ value at each point ($p < 0.001$***), with results in Table (12). However, there was a more significant effect of speaker on OQ value than register. There was a small interaction of register X speaker at every time index. Examining the data in Table 5, we notice that the modal and modal-tense register have different OQ values for speakers s1, s3, s5, and s6, but not for s2. There is also some variability in where certain OQ values differ between the modal and breathy-modal registers. For all speakers, there is a decrease in OQ value for the breathy-tense register, but its magnitude varies by speaker as well. While register has a strong effect on OQ value for all speakers, the speaker effect comes from individual differences in the timing and magnitude of changes in OQ.

Given that OQ values correlate with glottal aperture, we can conclude that the registers in Takhian Thong Chong are at least partly distinguished by differences in glottal aperture. The modal-tense register occurs with a smaller glottal opening than the modal register which occurs with a smaller glottal opening than the breathy-modal register. The breathy-tense register occurs with a quick change in glottal aperture size across the duration of the vowel.

Figure 2: Open Quotient and OQ Slope Data for 5 speakers
(Modal = solid, Breathy-Modal = dots, Modal-Tense = dashes, Breathy-Tense = dash-dot)

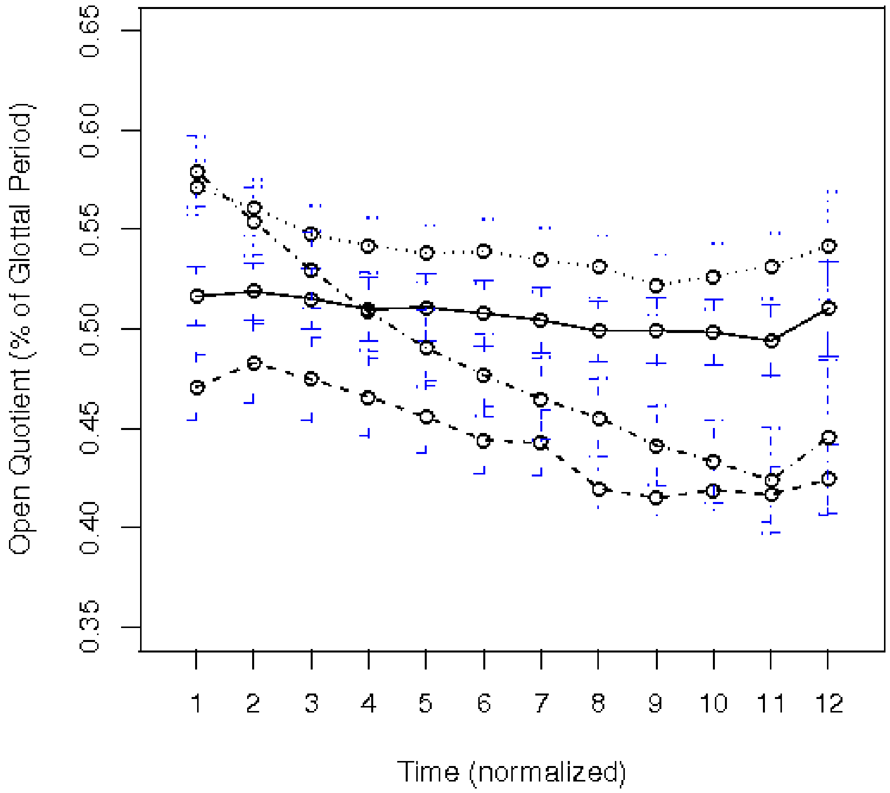

Table 5: OQ Values at Selected Time Points, by Speaker

	Modal				Modal -	Tense		
	t2	t5	t8	t11	t2	t5	t8	t11
s1	0.525	0.503	0.501	0.506	0.468	0.433	0.419	0.414
s2	0.467	0.443	0.433	0.432	0.448	0.439	0.416	0.413
s3	0.564	0.566	0.559	0.553	0.452	0.448	0.441	0.459
s5	0.582	0.618	0.591	0.603	0.614	0.627	0.583	0.559
s6	0.452	0.435	0.421	0.419	0.510	0.414	0.401	0.390

	Breathy -	Modal			Breathy -	Tense		
	t2	t5	t8	t11	t2	t5	t8	t11
s1	0.542	0.534	0.541	0.549	0.517	0.456	0.422	0.412
s2	0.517	0.478	0.450	0.445	0.502	0.437	0.396	0.363
s3	0.550	0.535	0.536	0.549	0.580	0.527	0.506	0.510
s5	0.637	0.599	0.613	0.602	0.617	0.598	0.562	0.500
s6	0.552	0.535	0.505	0.496	0.545	0.424	0.390	0.368

4 Acoustic Data

4.1 Method

Acoustic data was acquired using the same setup described in section (3.1) with the same speakers. However, all 7 speakers' acoustic data was usable. Acoustic recordings were originally sampled at 44.1 kHz. but downsampled to 16 kHz before analysis. A script was written to extract F0, H1-H2, H1-A1, H1-A2, and H1-A3 measures at 12 even time indices along the duration of each vowel along with its total duration. Spectral tilt was acquired by first calculating the position of F1, F2, and F3 with an LPC analysis. Maximum amplitude peaks were then extracted from ranges in a power spectrum within 10% of the frequency of a particular formant, i.e. if F2 = 2000 Hz., peak maxima were extracted from the 1800-2200 Hz. range. The amplitude value of the highest amplitude harmonic within these ranges corresponds to A1, A2, or A3. Two sets of formant reference values were used depending on the speaker's gender. For males, these reference values were F1 500 Hz., F2 1485 Hz., and F3 2475 Hz. For females the values were F1 550 Hz., F2 1650 Hz., and F3 2750 Hz. H1 and H2 were determined by taking the highest amplitude peak to within 10% of the fundamental and twice the fundamental, respectively. Data from all subjects were grouped together and statistically analyzed using R (2007).

Linear discriminant analysis (LDA) was performed on linear models containing 5 predictor variables for register at each time index: F0, H1-H2, H1-A1, H1-A2, and H1-A3. A two-way ANOVA determined that each of these measures was significant at each time index prior to their inclusion in the discrminant model. Wilk's Lambda and canonical correlations were calculated to determine the goodness of the discriminant model at each time index.

4.2 Spectral Tilt Results

The results of the LDA are shown in Table 6. The first two predictors correspond to the measures in the first linear discriminant model that account for the most variance. The *LD Proportion of Trace* is the proportion of between group variance that the first linear discriminant explains with respect to the total between group variance. Canonical Correlation is the percentage of variance in the data that is explained by the predictor variables. Wilk's lambda tests at each time index are given in Appendix A. All discriminant models were significant at each time index.

Table 6: Results of Linear Discriminant Analysis on Spectral Measures of Register

Time Index	Predictor 1	Coefficient	Predictor 2	Coefficient	LD Proportion of Trace	Canonical Correlation
1	H1-A3	0.078	H1-A2	0.064	76.7%	0.849
2	H1-A2	0.085	H1-A3	0.084	82.2%	0.848
3	H1-A3	0.084	H1-A2	0.079	78.5%	0.840
4	H1-A3	0.083	H1-A2	0.062	74.9%	0.834
5	H1-A3	0.076	H1-A2	0.068	72.1%	0.825
6	H1-A3	0.082	H1-A2	0.065	72.9%	0.812
7	H1-A3	0.073	H1-A2	0.057	74.1%	0.785
8	H1-A3	0.077	H1-H2	0.069	75.4%	0.784
9	H1-H2	0.091	H1-A3	0.077	74.8%	0.776
10	H1-A2	0.079	H1-A3	0.078	69.4%	0.767
11	H1-A2	0.067	H1-H2	0.063	64.7%	0.727
12	H1-A2	0.083	H1-A1	0.060	68.0%	0.722

Table 6 shows that the H1-A2 and H1-A3 spectral tilt measures are the best discriminators of register in Takhian Thong Chong. These account for the most variance within the first linear discriminant and were

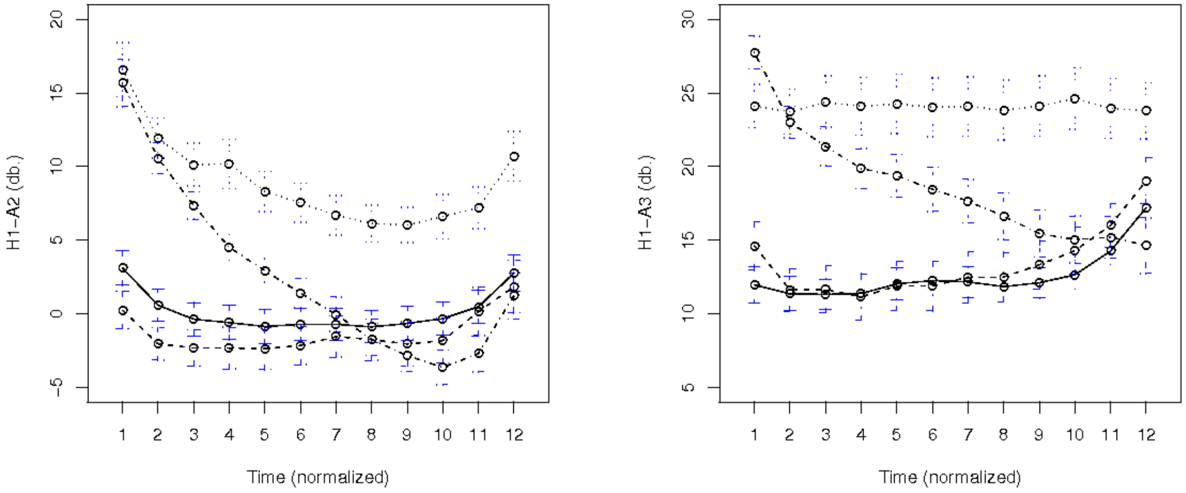

Figure 3: H1-A2 (left) and H1-A3 (right) spectral tilt measures
(Modal = solid, Breathy-Modal = dots, Modal-Tense = dashes, Breathy-Tense = dash-dot)

strongly correlated throughout the first half of the vowels' durations with adjusted R^2 values of 0.59, 0.56, 0.48, 0.44, 0.33, and 0.29 for the first six time indices. By comparison, there was little correlation between H1-A3 and H1-H2 at any point, reflected by a maximum adjusted R^2 value of 0.09. The predictor with the lowest coefficient at 7 time points was H1-A1. This particular measure was a poor predictor of the register contrast. The first linear discriminant accounts for a large proportion of the variance in register throughout the vowel duration. At each time index, the canonical correlation lies between 0.72 - 0.85, so the discriminant model can explain between 72% and 85% of the variance between the registers.

Plots of the H1-A3 and H1-A2 measures are shown in Figure 3 along with 95% confidence intervals. In both figures we observe that the breathy-modal register has a steeper spectral slope throughout its duration than any of the other registers. The modal and tense registers have very similar H1-A2 and H1-A3 values throughout the duration of the vowel. The breathy-tense register begins with steep spectral slope but rapidly becomes more tense throughout its duration. While the H1-A2 measure shows some change in spectral slope for the breathy-modal register, no such change is apparent in the H1-A3 measure.

A two-way ANOVA was performed on H1-A3 with register, speaker, and vowel as factors, shown in table (7. The results show the most significant effect for register at all time indices, followed by significant effects of both speaker and vowel quality. There were also significant interactions between all these factors (not shown) at a $p < 0.01$ level at every time index. These results suggest that the strongest factor determining H1-A3 value is the vowel's register. While both speaker identity and vowel quality influence the formant position, these factors were not as strong. Individual differences between the different registers' H1-A3 values were determined via Welch two-sample t-tests, shown in the appendix. Results from these tests show that the each of the registers are distinct from one another except for the modal-tense and the modal register. The breathy-tense register does not significantly differ from the breathy register at time index 2 while it does not significantly differ from the modal-tense or modal register at time index 11.

Even though H1-A3 and H1-A2 are significant measures distinguishing register in Takhian Thong Chong, they do not distinguish between the modal and the modal-tense register. Rather, it seems that these spectral tilt measures best distinguish the phonation types which contrast in terms of breathiness. The results of the LDA show that both H1-H2 and H1-A1 account for the least overall variance as spectral tilt measures. However, these particular measures may show some differences between the registers that are not accounted

Table 7: Results of Two-way ANOVA on H1.A3 with selected predictors.
All are significant at a $p < 0.001$ level unless otherwise noted.

Time Index	Register	Speaker	Vowel
1	F(3, 317) = 422.8	F(6, 317) = 98.7	F(5, 317) = 34.7
2	F(3, 367) = 415.9	F(6, 367) = 148.2	F(5, 367) = 50.9
3	F(3, 367) = 392.6	F(6, 367) = 150.1	F(5, 367) = 99.7
4	F(3, 367) = 386.8	F(6, 367) = 146.9	F(5, 367) = 146.9
5	F(3, 367) = 287.4	F(6, 367) = 134.4	F(5, 367) = 151.0
6	F(3, 367) = 267.4	F(6, 367) = 131.3	F(5, 367) = 152.6
7	F(3, 367) = 251.9	F(6, 367) = 126.4	F(5, 367) = 163.0
8	F(3, 367) = 243.1	F(6, 367) = 113.1	F(5, 367) = 169.7
9	F(3, 367) = 197.5	F(6, 367) = 98.2	F(5, 367) = 132.1
10	F(3, 367) = 199.4	F(6, 367) = 86.4	F(5, 367) = 136.3
11	F(3, 355) = 149.6	F(6, 355) = 69.6	F(5, 355) = 125.3
12	F(3, 305) = 92.8	F(6, 305) = 29.9	F(5, 305) = 89.7

for in the other measures. Both H1-A1 and H1-H2 are shown in Figure 4.

From the H1-A1 data, we observe that spectral slope on the modal register is not as steep as on the modal-tense register. Instead, the modal register occupies an intermediate position with respect to the spectral slope values of both the breathy register and the modal-tense register. From the H1-H2 data, we observe that the spectral slope values given for the modal register are lower (flatter) than those of the breathy-modal register at time index 1-4, but overlap with those of the breathy-modal register from time index 5-12. The tense-modal and breathy-tense registers overlap in H1-H2 value for a majority of their duration, but not at time index 1. Both the H1-A1 and H1-H2 measures show a distinction between the modal-tense and modal registers. This is most clear in the H1-H2 measure, where registers with glottal tension group together while those lacking glottal tension do not. While we observed that the H1-A3 and H1-A2 measures were closely correlated, this was not found for the H1-H2 and H1-A1 measures. The maximum adjusted $R^2 = 0.21$, where $R^2 < 0.05$ at most of the time indices. Individual differences between the different registers' H1-H2 values were determined via Welch two-sample t-tests, shown in the appendix. These tests show that the H1-H2 measure significantly distinguishes between modal-tense and modal register, the modal-tense and breathy register, the breathy-tense and modal register, and the breathy-tense and breathy-modal register. The breathy-modal/modal and tense/breathy-tense contrasts do not significantly vary with respect to the H1-H2 measure.

4.3 Summary of Spectral Tilt Data

The results from the LDA show that both H1-A3 and H1-A2 are the best predictors of the register contrast within the first linear discriminant. Overall spectral tilt differences between registers were of greater magnitude with these measures than with measures like H1-H2 and H1-A1. However, there is an interesting division of labor between distinct spectral tilt measures. The H1-A3 and H1-A2 measure distinguish registers containing breathiness, which are not distinguished using the H1-H2 or H1-A1 measure. The H1-H2 measure distinguishes registers containing glottal tension which are *not* distinguished using the H1-A3 or H1-A2 measure.

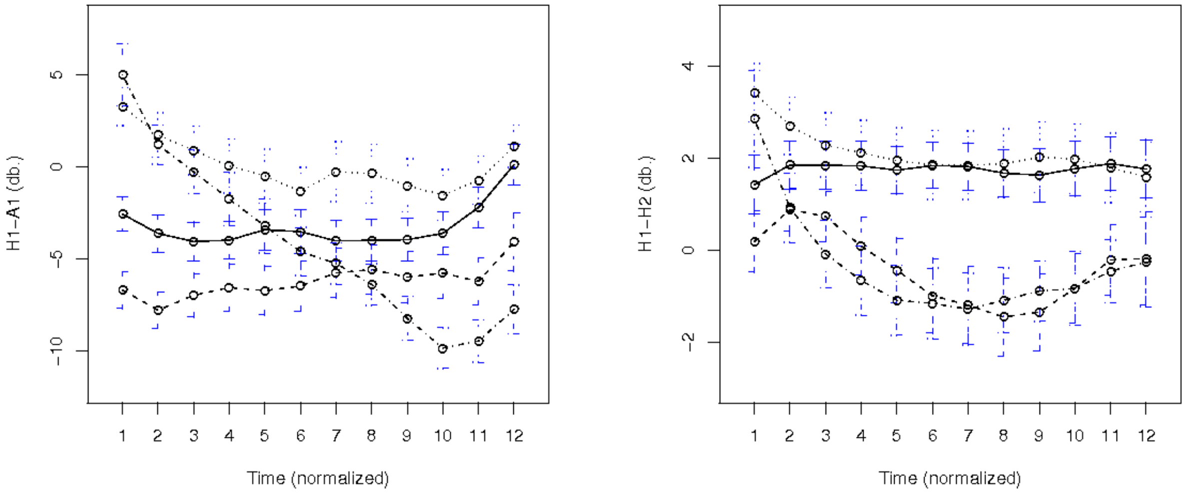

Figure 4: H1-A1 (left) and H1-H2 (right) spectral tilt measures
(Modal = solid, Breathy-Modal = dots, Modal-Tense = dashes, Breathy-Tense = dash-dot)

4.4 Pitch and Duration Results

4.4.1 Pitch

Pitch data from Takhian Thong Chong is given in Figure 5.[5] The modal-tense register is realized with a high rising-falling pitch contour that is approximately 30 Hz. higher than the other registers' pitch values throughout its duration. The other registers are all within about 20 Hz. of each other. The breathy-tense register has higher overall pitch than the breathy-modal and modal registers. The modal register has the lowest overall pitch. These results are similar to the findings in Thongkum (1988) for the Thung Kabin dialect where the modal-tense and breathy-tense register have higher pitch while the breathy-modal and modal registers have a lower pitch.

Table 8: Results of Two-way ANOVA on Pitch.
All are significant at a $p < 0.001$ level unless otherwise noted.

Time Index	Register	Speaker	Register X Speaker
2	F(3, 416) = 114.8	F(6, 416) = 99.3	F(18, 416) = 3.4
5	F(3, 416) = 182.6	F(6, 416) = 117.4	F(18, 416) = 5.4
8	F(3, 416) = 163.7	F(6, 416) = 139.9	F(18, 416) = 5.0
11	F(3, 404) = 47.2	F(6, 404) = 83.5	F(18, 404) = 2.9

The results from a two-way ANOVA at four time intervals (2, 5, 8, 11) reveal a significant effect of register on pitch at all time points with $p < 0.001$. These results are given in Table 8. There was a strong effect of speaker on pitch along with an interaction between speaker and register. Individual differences between the different registers' pitch values were determined via Welch two-sample t-tests, shown in the appendix.

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[5] Except for the modal register, each register is realized with a rising-falling pitch contour. This may originate from the recording context where tokens were elicited in isolation. However, the frequency and magnitude of the pitch contours is distinct.

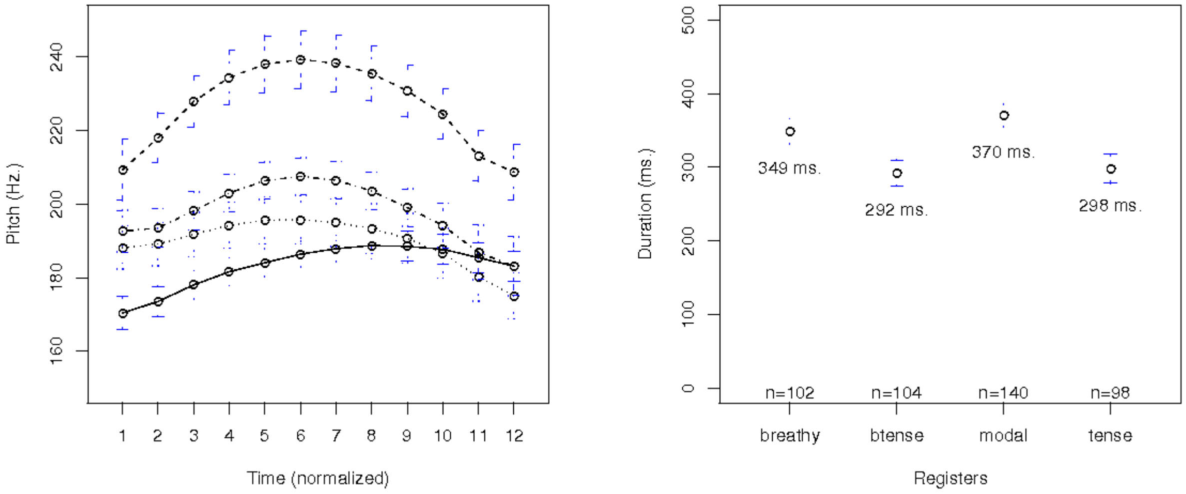

Figure 5: Pitch (left) and Duration (right)
(Modal = solid, Breathy-Modal = dots, Modal-Tense = dashes, Breathy-Tense = dash-dot)

These data show that each register is significantly different from the modal-tense register in pitch throughout the vowel. The modal register is significantly different from the breathy-tense register throughout the vowel duration, but only significantly different from the breathy-modal register at time indices 2 and 5 (the first half of the vowel). The breathy-modal and breathy-tense registers are not significantly different in terms of pitch.

4.4.2 Duration

From the duration data in Figure 5, we observe that both breathy-tense and modal tense vowels have shorter duration than breathy-modal and modal vowels. However, vowel duration can be influenced by other factors, such as coda type and vowel quality (Keating 1985). Since other factors that may cause a change in vowel duration, we must determine how much register plays a role compared to them. Results from a two-way ANOVA with register, speaker, and vowel quality as factors on vowel duration demonstrated a significant effect of register, F(3, 365) = 141.2, $p < 0.001$ ***; speaker, F(6, 365) = 351.9, $p < 0.001$ ***; and vowel quality, F(4, 365) = 6.8, $p < 0.001$ ***. There were also significant interactions between each of these on vowel duration: register X vowel quality, F(4, 365) = 28.5, $p < 0.001$ ***; register X speaker, F(18, 365) = 5.8, $p < 0.001$ ***; and vowel quality X speaker, F(24, 365) = 7.7, $p < 0.001$ ***. Finally there was an interaction between all three factors, F(19, 365) = 7.2, $p < 0.001$ ***. While speaker is the strongest factor accounting for the variance in duration, register was also strongly significant. Interestingly, the effect of vowel quality on vowel duration was not very strong. This is probably due to the fact that most vowels in the data set are mid or low vowels. We might expect a vowel quality effect on duration to be more noticeable if the data set had contained more words with high vowels, as they tend to have the greatest influence on duration (Keating 1985).

4.5 Summary of Pitch and Duration Data

While the best predictors of register in the LDA were those relating to spectral tilt, pitch also significantly varied with respect to register. In general, the modal-tense register is realized with substantially higher pitch than the other registers throughout its duration while the modal register is realized with the lowest pitch.

The breathy-tense and breathy-modal registers have intermediate pitch values that are significantly different from both the modal and modal-tense registers, but not significantly different from each other. The duration data show that the registers containing glottal tension occur with shorter vowels than those registers lacking glottal tension.

5 Analysis and Discussion

5.1 Spectral Tilt and Open Quotient Correlation

To examine the relationship between the OQ data given in Section 3.2 and the spectral tilt measures in Section 4.2, I calculated the degree of correlation between them. The spectral tilt data was truncated so that the data frames had matched observations, as the OQ data contained two fewer speakers than the spectral tilt data. A correlation matrix with adjusted R^2 values is given in Table 9

Table 9: Correlation Comparison between spectral tilt measures, pitch, and OQ.
Values given as adjusted R^2.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
OQ & H1-H2	0.34	0.30	0.31	0.36	0.40	0.39	0.42	0.42	0.37	0.37	0.45	0.46
OQ & H1-A1	0.26	0.07	0.18	0.14	0.13	0.11	0.13	0.14	0.18	0.17	0.19	0.28
OQ & H1-A2	0.22	0.20	0.17	0.11	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.03
OQ & H1-A3	0.16	0.22	0.20	0.19	0.18	0.14	0.15	0.11	0.09	0.06	0.06	0.01
OQ & F0	0.01	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.04	0.11	0.01

OQ is more closely correlated to the H1-H2 measure than any of the other spectral tilt measures at all points in time. Two conclusions can be drawn from this. First, since H1-H2 distinguishes the phonation types containing glottal tension from those without it, OQ is by extension also a good predictor of the degree of glottal tension. Second, the lack of correlation between the mid-band spectral tilt measures and the OQ data suggest that changes in spectral tilt within broader ranges of the spectrum are not the direct result of changes in glottal tension. Rather such changes are perhaps indirectly the result of aerodynamic changes in the vocal tract which influence the amplitude of formants within broader regions of the spectrum.

5.2 Data Comparison

Table 10 shows the acoustic and laryngographic characteristics of each of the registers in Takhian Thong Chong. The OQ measure relates to different spectral tilt measures in a complementary way. Registers with low OQ values are correspond with those with flatter spectral tilt (low) within the lower region of the spectrum. As a result, the measures H1-H2 and H1-A1 uniquely capture the differences between registers lacking glottal tension and those containing it. The other registers are not as strongly distinguished using these measures though. The relationship between low OQ value and low H1-H2 value is reflected in the correlation between these two measures given in Tabel 9.

The modal-tense, breathy-modal, and breathy-tense registers have declining OQ values throughout the vowel duration. This seems to also correspond to a fall in H1-H2 value. Interestingly, this is not well-reflected in the H1-A2 or H1-A3 measures where the breathy-modal and breathy-tense registers are relatively level throughout their duration.

Registers with higher OQ values also correspond to those with a steeper (high) spectral tilt within a broader spectral range. The measures H1-A2 and H1-A3 uniquely capture the differences between registers lacking breathiness and those containing it. These measures may be used to distinguish between all registers *except* between the modal and modal-tense registers. While this relationship is not directly observed in the

Table 10: Significant Articulatory and Acoustic Correlates of Register

	Modal	Modal-Tense	Breathy-Modal	Breathy-Tense
OQ Value	Intermediate Level	Low Declining	High Declining	High to Low Declining
H1-A3	Low Slight rise	Low Slight rise	High Level	High to Low Falling
H1-A2	Low Rising	Low Rising	High Falling	High to Low Falling
H1-A1	Intermediate Level	Low Slight rise	High Initial Fall	High to Low Falling
H1-H2	High Level	Low Falling	High Initial Fall	High to Low Falling
Pitch	Low Slight rise	Intermediate Rising-Falling	Intermediate Rising-Falling	High Rising-Falling
Duration	Longer	Shorter	Longer	Shorter

correlation matrix in Table 9, increasing OQ may have the indirect result of changing aerodynamic conditions which causes a decrease in amplitude of formants within the spectrum.

Certain spectral tilt measures seem to vary significantly with respect to pitch. At selected time indices (2, 5, 8, 11) across the vowel duration, two-way ANOVAs were performed with spectral tilt measures as factors. The results in Table 11 show that each spectral tilt measure varies somewhat with pitch, but no particular measure seems to correlate closely with pitch at all time points. For instance, the modal-tense register is produced with a decreasing OQ values and spectral tilt at the end of the vowel, yet these values are uncorrelated with the higher overall pitch and pitch contour present with this register. We may conclude that pitch can be influenced slightly by changes in phonation type but the pitch contours present with different registers are not simply byproducts of changes in glottal aperture.

Table 11: Results of Two-way ANOVA on Pitch with Spectral Tilt Factors

Time Index	H1-H2	H1-A1	H1-A2	H1-A3
2	$F(1, 428) = 20.1$ $p < 0.001$ ***	$F(1, 428) = 2.3$ $p = 0.13$	$F(1, 428) = 10.2$ $p < 0.005$ **	$F(1, 428) = 64.4$ $p < 0.001$ ***
5	$F(1, 428) = 51.8$ $p < 0.001$ ***	$F(1, 428) = 34.2$ $p < 0.001$ ***	$F(1, 428) = 0.3$ $p = 0.61$	$F(1, 428) = 14.3$ $p < 0.001$ ***
8	$F(1, 428) = 60.4$ $p < 0.001$ ***	$F(1, 428) = 42.6$ $p < 0.001$ ***	$F(1, 428) = 0.4$ $p = 0.53$	$F(1, 428) = 5.9$ $p < 0.05$ *
11	$F(1, 416) = 2.5$ $p = 0.11$	$F(1, 416) = 9.1$ $p < 0.005$ **	$F(1, 416) = 5.3$ $p < 0.05$ *	$F(1, 416) = 2.8$ $p = 0.10$

5.3 Discussion

The results from the comparison between OQ and spectral tilt suggest that there is a one to many interaction between the proportion of the glottal cycle that is open and its acoustic consequences on the speech signal in Chong. The acoustic correlates of Chong register include mid-band and narrow-band spectral slope, changes in spectral slope, pitch, and to a lesser degree, duration. Registers with increased glottal tension, or low OQ, are best distinguished from the other registers with narrow-band spectral slope (H1-H2), pitch, and duration. Registers with breathiness, or high OQ, are best distinguished from the others with mid-band spectral slope measures and changes in spectral slope. These findings are in agreement with Blankenship (2002) and Esposito (2006) who found that H1-H2 was a poor discriminator of the modal and breathy registers in Chong. The results of a LDA reveal that H1-A3 and H1-A2 better discriminate among all registers in the language, including breathy-modal and modal registers. Whereas the previous studies did not address the utility of different measures in distinguishing all four registers in the language, this study has attempted to do so while also comparing spectral tilt measures to changes in the vibratory cycle of the vocal folds.

The breathy-tense and the breathy-modal registers are realized with increased OQ values after the onset consonant release in Chong while the breathy-tense and modal-tense registers are realized with decreased OQ values at the end of the vowel. These findings agree with Edmondson (1997) who found greater glottal airflow at the beginning of the breathy registers which gradually diminished and low amplitude glottal airflow at the end of tense register vowels. Thongkum (1991) makes a similar prediction regarding increasing glottal tension on these registers. Contra Blankenship (2002), breathiness does not increase on the breathy-modal vowels.

The increased correlation between OQ and H1-H2 and the lack of correlation between OQ and other spectral tilt measures suggests that EGG methods may only be useful for distinguishing between two glottal states: tense and non-tense. As many register languages contain only two phonation types, EGG analysis is probably useful for them. However, in a language like Chong, with four phonation types, differences among all registers may not be *directly* observable from the EGG signal. H1-A3 and H1-A2 are strong discriminators of register in Chong. However, if amplitude differences calculated from these measures are not correlated with OQ, some other mechanism must be responsible for the decreases in harmonic amplitude present in breathy-modal and breathy-tense phonation. The decreased excitation of resonance present with larger OQ values may not explain decreased formant amplitude. Instead, the presence of broadband spectral energy may be more responsible for causing substantial differences in H1-A2 and H1-A3.

The pitch data here suggests a weak association between phonation type and pitch. We might expect a close correlation between increased glottal tension and pitch as both may involve laryngeal raising. The modal-tense register is, in fact, realized with the highest pitch of all the registers, similar to findings by Thongkum (1988) for Thung Kabin Chong. However, on this register and others, changes in the pitch do not correspond to changes in glottal aperture. While the modal-tense register occurs with a rising-falling pitch contour, OQ values decrease throughout its duration. The same is true for the other registers. The H1-H2 values are the most closely correlated with the pitch changes, as shown in Figure 11. This is in agreement with Esposito (2006) who mentions that pitch tends to most closely correlate with H1-H2. However, there are substantial differences between the pitch contours and the H1-H2 contour. While the breathy-tense and modal-tense registers virtually overlap in H1-H2 value, the modal-tense register is realized with substantially higher pitch than the breathy-tense register. The contour of each register's pitch resembles its H1-H2 trajectory, however the relative pitch level seems unrelated to H1-H2 values.

Phonation type influences pitch in many languages (Silverman 1997a), so we would expect changes in voice quality to correlate with changes in pitch. However, the presence of pitch that is uncorrelated with phonation type in Chong suggests that pitch changes are not simply phonetic by-products of phonation type. While these pitch contours may be phonologically associated with particular registers, they are distinct phonetic correlates of the register contrast.

While the phonological vowel length contrast must be a strong predictor of observed phonetic vowel duration, register is also significant. While Thongkum (1988) does not find vowel duration to be a correlate of the register contrast in Thung Kabin Chong, it distinguishes the registers with glottal tension in Takhian Thong Chong from those lacking it. Both modal-tense and breathy-tense vowels have a similar shorter duration than the modal or breathy-modal vowels. Fischer-Jørgensen (1967) and Kirk et al. (1984) mention that breathy vowels in Gujarati and Jalapa Mazatec have longer duration than modal or creaky phonation. Gordon and Ladefoged work (2001) mention that the overall duration of vowels with non-modal phonation is longer than those with modal phonation. An explanation for this pattern is given in Silverman (1997b) which states that breathy vowels in languages are longer so that speakers have additional time to perceive the voice quality on the vowel.

However, there is perhaps a historical reason for the development of longer phonetic duration on breathy vowels and shorter phonetic duration on tense vowels. Breathy vowels often derive from historically aspirated initial stops. In these cases, the loss of the duration of aspiration following the stop may cause the vowel to undergo compensatory lengthening. As a result, a longer vowel occurs with breathy phonation. On the other hand, glottal tension often derives from a historical glottal stop at the end of the vowel. Final glottal stops may cause vowel shortening if the vowel is shorter before voiceless stops as a general phonetic trend. This is true in a variety of languages (Chen 1970). Rather than suggesting that vowel duration of non-modally phonated vowels is synchronically-related to some active parameter of enhancement, it may be directly motivated by its historical origin.

6 Conclusion

The fact that Chong has a 4-way contrast in register makes it exceptional from a typological viewpoint. The results of both an EGG and an acoustic phonetic analysis of the register distinction in this language add support to the view that the specific timing relationship of laryngeal configurations across the syllable is relevant in marking phonological distinctions in languages of the world. The findings show that H1-H2 best correlates with changes in open quotient, while mid-band spectral tilt measures do not. In a complex register language like Chong, a number of acoustic parameters distinguish the different registers. H1-H2 was found to distinguish between the presence and absence of increased glottal tension while H1-A3 distinguished between the presence and absence of breathiness.

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Appendices

Table 12: Open Quotient Statistics

Time Index	Effect of Register	Effect of Speaker	Speaker X Register
t1	F(3, 264) = 52.7	F(4, 264) = 20.1	F(12, 264) = 2.9
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.005$ **
t2	F(3, 272) = 30.8	F(4, 272) = 43.8	F(12, 272) = 4.7
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t3	F(3, 274) = 23.3	F(4, 274) = 64.3	F(12, 274) = 4.5
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t4	F(3, 272) = 27.9	F(4, 272) = 86.8	F(12, 272) = 6.8
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t5	F(3, 275) = 43.7	F(4, 275) = 125.7	F(12, 275) = 8.1
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t6	F(3, 274) = 63.8	F(4, 274) = 146.9	F(12, 274) = 6.7
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t7	F(3, 275) = 73.5	F(4, 275) = 175.4	F(12, 275) = 7.8
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t8	F(3, 273) = 82.6	F(4, 273) = 170.2	F(12, 273) = 7.5
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t9	F(3, 273) = 74.6	F(4, 273) = 138.9	F(12, 273) = 6.1
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t10	F(3, 272) = 69.2	F(4, 272) = 110.8	F(12, 272) = 4.8
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t11	F(3, 232) = 71.6	F(4, 232) = 99.2	F(12, 232) = 3.8
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
t12	F(3, 118) = 35.2	F(4, 118) = 66.7	F(12, 118) = 1.8
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.05$ *

Table 13: Wilk's Lambda

Time Index	Wilk's Value	F-Statistic	Significance
1	0.28	F(3, 384) = 41.0	$p < 0.001$ ***
2	0.28	F(3, 440) = 46.9	$p < 0.001$ ***
3	0.29	F(3, 440) = 44.7	$p < 0.001$ ***
4	0.31	F(3, 440) = 43.2	$p < 0.001$ ***
5	0.32	F(3, 440) = 40.9	$p < 0.001$ ***
6	0.34	F(3, 440) = 38.4	$p < 0.001$ ***
7	0.38	F(3, 440) = 33.3	$p < 0.001$ ***
8	0.39	F(3, 440) = 33.0	$p < 0.001$ ***
9	0.40	F(3, 440) = 31.8	$p < 0.001$ ***
10	0.41	F(3, 437) = 30.3	$p < 0.001$ ***
11	0.47	F(3, 428) = 24.5	$p < 0.001$ ***
12	0.48	F(3, 372) = 20.7	$p < 0.001$ ***

Table 14: T-tests of H1-A3 Differences at selected time indices.

Comparison	t2	t5	t8	t11
modal vs. tense	$t = -0.27$	$t = 0.14$	$t = -0.66$	$t = -1.98$
	$p = 0.78$	$p = 0.89$	$p = 0.51$	$p = 0.05$
modal vs. breathy	$t = -12.8$	$t = -10.6$	$t = -10.5$	$t = -8.6$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
modal vs. br-tense	$t = -14.6$	$t = -8.0$	$t = -5.1$	$t = -1.1$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p = 0.27$
tense vs. breathy	$t = -11.4$	$t = -9.4$	$t = -8.5$	$t = -6.3$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
tense vs. br-tense	$t = -12.5$	$t = -6.7$	$t = -3.6$	$t = 0.78$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p = 0.44$
breathy vs. br-tense	$t = 0.75$	$t = 3.9$	$t = 5.6$	$t = 7.0$
	$p = 0.45$	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***

Table 15: T-tests of H1-H2 Differences at selected time indices.

Comparison	t2	t5	t8	t11
modal vs. tense	$t = 2.7$	$t = 5.0$	$t = 6.2$	$t = 4.3$
	$p < 0.01$ **	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
modal vs. breathy	$t = -2.1$	$t = -0.47$	$t = -0.46$	$t = 0.19$
	$p = 0.04$	$p = 0.64$	$p = 0.64$	$p = 0.85$
modal vs. br-tense	$t = 2.0$	$t = 6.1$	$t = 6.3$	$t = 5.2$
	$p = 0.05$	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
tense vs. breathy	$t = -4.7$	$t = -4.7$	$t = -5.8$	$t = -3.7$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
tense vs. br-tense	$t = -0.08$	$t = 1.2$	$t = -0.66$	$t = 0.48$
	$p = 0.93$	$p = 0.21$	$p = 0.51$	$p = 0.63$
breathy vs. br-tense	$t = 3.6$	$t = 5.8$	$t = 5.7$	$t = 4.4$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***

Table 16: T-tests of Pitch Differences at selected time indices.

Comparison	t2	t5	t8	t11
modal vs. tense	$t = -11.2$	$t = -12.4$	$t = -11.2$	$t = -6.9$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
modal vs. breathy	$t = -4.3$	$t = -3.1$	$t = -1.2$	$t = 1.3$
	$p < 0.001$ ***	$p < 0.005$ **	$p = 0.23$	$p = 0.19$
modal vs. br-tense	$t = -5.9$	$t = -7.0$	$t = -4.7$	$t = -0.34$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p = 0.73$
tense vs. breathy	$t = 6.4$	$t = 8.4$	$t = 8.4$	$t = 6.9$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
tense vs. br-tense	$t = 5.7$	$t = 6.8$	$t = 7.0$	$t = 5.2$
	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***	$p < 0.001$ ***
breathy vs. br-tense	$t = -1.1$	$t = -2.6$	$t = -2.4$	$t = -1.3$
	$p = 0.27$	$p < 0.01$ **	$p = 0.017$ ns	$p = 0.18$