Chanthaburi Khmer vowels: Phonetic and phonemic analyses*

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0. Introduction

In his survey of 1976, Huffman classified 15 Mon-Khmer languages into five subgroups: the conservative, the transitional, the register, the restructured and the tonal groups. Conservative languages preserve the PI contrast of proto Mon-Khmer consonants. These include some Bahnaric languages. In transitional languages, the voiced-voiceless contrast becomes a tense-lax contrast with subphonemic register differentiation in the vowels after stops, but not after continuants. According to Huffman, these include some Katuic languages. The pure register languages have complete merger of the stops, with a complete register contrast in the vowels. These include Monic languages and some Katuic language. The restructured languages, including Khmer, have a complete phonetic and phonological merger of initial stops, with two vowel subsystems characterized by a change in absolute articulatory position and/or diphthongization. In the tonal languages, including Vietnamese, the devoicing of the proto voiced-voiceless contrast results in a doubling of tone contrasts.

Not known to Huffman at the time was a dialect of Khmer spoken in Chanthaburi province of Thailand. Although this dialect has been studied by Thongkum and Diffloth since the 1980's (Diffloth, p.c.), to my knowledge no detailed information on this dialect has been published yet. So this paper seeks to give a report on the phonetic and phonological vowel system of Chanthaburi Khmer. This dialect of Khmer preserves the breathy and clear voice quality distinction that has been claimed to exist in the history of Khmer.

Interestingly, unlike other modern dialect of Khmer, Chanthaburi Khmer contains some phonetic characteristics that are similar to those of a pure registered, and some characteristics of a transitional language, as well as the expected characteristics of a restructured language. The existence of phonemic contrast between breathy and clear phonation in certain vowels of Chanthaburi Khmer strongly suggests that ancient Khmer was probably a register language, contrary to Huffman's classification as a restructured language.

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The paper starts with an acoustic analysis of the breathy and clear vowel characteristics. This is followed by a perceptual investigation. Finally, a phonetic and phonemic analysis of the entire vowel system of Chanthaburi Khmer is presented.

I. Acoustic and perception analyses

The goal of this section is to provide phonetic evidence for the existence of breathy and clear voice quality contrast in the vowel system of Chanthaburi Khmer. It will be shown that breathy vowels in Chanthaburi Khmer have some acoustic characteristics that are consistent with the acoustic characteristic of breathy voice phonation found in other studies. These acoustic correlates of breathiness are outlined below.

1. Acoustic correlates of breathy voice

A. Amplitude of the First Harmonic

Breathiness is thought to be due to incomplete and non-simultaneous glottal closure during the 'closed' phase of the phonatory cycle (Fairbank 1940; Zemlin 1968; Hillenbrand et al. 1990; Klatt & Klatt 1990; Hillenbrand et al. 1994, 1996). This results in a near sinusoidal shape of glottal waveforms which is believed to be responsible for increases in relative amplitude of the first harmonic (H1) (Klatt & Klatt 1990; Hillenbrand 1994, 1995). However, to assess whether there is an increase in the H1 amplitude or not, H1 amplitude must be compared with some reference that takes into account the recording level such as: (a) rms power of the vowel; (b) amplitude of the second harmonic (H2); or (c) amplitude of the first formant (F1). In this study, the amplitude of H2 was used as a reference. However, due to a potential 'boosting effect' of the F1 amplitude on the amplitude of H1 and H2, the amplitudes of both H1 and H2 were corrected using the algorithm provided by Hanson (1995). The difference between the H1 and H2 amplitudes (*H1-*H2) is taken to be a reasonable measure of open quotient and is expected to be greater for a breathy vowel than for a clear vowel.

B. Spectral tilt

The non-simultaneous closure during the production of breathy vowels results in a more gradual cessation of airflow and causes an additional decrease in the amplitude of the harmonics in the higher frequencies region resulting in an increase in the spectral tilt. That is, there is a decrease in the amplitude of harmonics at higher frequencies of the spectrum. According to Hanson (1995), this change in spectral tilt in breathy voice is reflected by relative decrease of the most prominent harmonic in the third formant region (A3). Thus H1-A3 can be taken as a reasonable measure of spectral tilt. However, due to a potential boosting effect of the third formant (F3) on A3, the amplitude of A3 was corrected using Hanson's algorithm. The difference between the amplitude of *H1 and *A3 (*H1-*A3) is expected to be greater for breathy vowels than for clear vowels.

C. First formant (F1) bandwidth

An incomplete glottal closure (a glottal chink) during the closed phase of a breathy phonation may result in an increased losses at the glottis and it results primarily in a greater first formant bandwidth (Klatt & Klatt 1990). The difference in the amplitude of *H1 and that of the most prominent harmonic in the F1 region (A1) has been used as an indicator of F1 bandwidth (Klatt & Klatt 1990; Hanson, 1995). An increase in the F1 bandwidth causes a reduction in the peak amplitude of the F1, resulting in a less prominent A1. Thus the difference between *H1 and A1 (*H1-A1) amplitudes is expected to be greater in a breathy phonation than in a clear phonation.

D. Harmonic-to-Noise Ratio (HNR)

The existence of a glottal chink during a breathy phonation could also result in noise generation at the glottis. This is reflected as noise or aperiodicity in the spectrum at higher frequencies. The harmonic-to-noise ratio could thus be used as a possible measure for breathiness. In this study, HNRs at seven different frequency ranges (from 60 to 5,000 Hz) and at three locations (30%, 50% and 70%) in the vowels were measured using de Krom (1993)'s HNR algorithm.

2. Experiment 1: Acoustic measurements

A. Speakers

Two native speakers (one male, one female) of Khmer spoken at Thung Kabin village of Chanthaburi Province, Thailand served as speakers for this experiment. The male speaker was approximately 40 years of age and the female speaker was 64 years of age at the time of recording. Both speakers reported no speech or hearing impairment.

B. Stimuli

Five breathy and clear vowels (near) minimal pairs spoken by the two speakers are used for the experiment. An attempt was made to use the same vowel quality for both speakers. Two tokens of each of the five vowel pairs from each speaker were used.

1. Female speaker's stimuli

Breathy		Clear	
[km̩pɛ̤ːk]	'bald'	[cɛːk]	'to give out'
[c̤i̤ɛh]	'to avoid'	[ciɛh]	'a kind of lizard'
[pre̤ːŋ]	'ancient'	[preːŋ]	'oil'
[p^{h}lo̤u]	'buttock'	[p^{h}lou]	'way, path'
[pə̤ːp]	'to meet accidentally'	[pəːp]	'sound of a barking deer'

2. Male speakers stimuli

Breathy		Clear	
[kmpɛ̤ːk]	'bald'	[pɛːt]	'eight'
[pʰlo̤u]	'buttock'	[pʰlou]	'way, path'
[pɔ̤ːp]	'to meet accidentally'	[pɔːp]	'sound of a barking deer'
[pr̤iɛ̤p]	'pigeon'	[priɛp]	'to compare'
[pɔ̤ːŋ]	'egg'	[pɔoŋ]	'a balloon'

C. Acoustic parameters measured

The following measurements were used for analysis:

1. *H1-*H2: The difference between the corrected amplitude of the first harmonic, *H1, and the second harmonic, *H2 in dB measured at 30%, 50% and 70% in the vowel was used as an indicator for open quotient.

2. *H1-A1: The difference between the corrected amplitude of the first harmonic, *H1, and the peak corresponding to the first formant, A1, in dB at three locations in the vowel (30%, 50%, 70%) was taken as an indicator for first formant bandwidth.

3. *H1-*A3: The difference between the corrected amplitude of the first harmonic, *H1, and the corrected amplitude peak corresponding to the third formant, *A3, in dB at three locations in the vowel (30%, 50% and 70%) was taken as measure of spectral tilt.

4. Vowel HNRs at seven frequency ranges (60-500, 60-1,000, 1-2,000, 2-3,000, 3-4,000, 4-5000, and 60-5,000Hz) at 30%, 50% and 70% in the vowels were taken as measure of additive noise.

5. Vowel average RMS amplitude.

6. Vowel Average fundamental frequency (F0).

7. Vowel duration.

D. Results

Results of the acoustic measurements of breathy and clear vowels spoken by both the male and the female speakers are reported in Table 1.

Table 1. Summary of the acoustic characteristics

speaker	Female			Male		
Acoustic parameters	Breathy vowels	Clear vowels		Breathy vowels	Clear vowels	
V. duration	264.2	231.8	-	235.7	213.5	-
V. intensity	76.6	72.5	**	79.2	77.8	**
Average F0	135.7	129.5	-	108.2	105.5	
*H1-*H2 at 30%	4.38	-1.24	**	-6.82	-11.08	**
*H1-*H2 at 50%	3.72	-1.44	**	-7.10	-11.16	**
*H1-*H2 at 70%	3.07	-.80	**	-8.87	-10.97	**
*H1-*A3 at 30%	4.26	9.80	-	-14.38	-18.63	-
*H1-*A3 at 50%	14.18	11.39	-	-14.35	-18.87	-
*H1-*A3 at 70%	15.89	11.97	**	-9.97	-9.50	-
*H1-A1 at 30%	-3.93	-8.69	**	-14.38	-18.63	**
*H1-A1 at 50%	-4.73	-9.42	**	-14.35	-18.87	**
*H1-A1 at 70%	-6.15	-7.40	-	-16.10	-18.00	-
HNR 60-5,000 Hz	17.88	17.68	-	21.31	18.46	-
HNR 60-1,000 Hz	34.20	31.05	-	34.85	34.44	-
HNR 500-1,000 Hz	45.78	41.73	-	45.21	44.84	-
HNR 1-2,000 Hz	28.67	26.91	-	30.97	29.27	-
HNR 2-3,000 Hz	20.45	19.80	-	24.76	21.18	-
HNR 3-4,000 Hz	14.32	15.67	-	18.88	14.86	*√
HNR 4-5,000 Hz	10.99	13.15	-	16.86	11.26	**√

* = Significant at p <.05
** = Significant at p <.01
**√ = Significant but in unexpected direction

1. Female speaker

Results of the acoustic analyses show that the breathy and clear vowels produced by the female speaker differed in several dimensions. Breathy vowels were produced with a significantly greater intensity than clear vowels (76.6 dB vs. 72.5 dB, $t(9) = 3.35$, $p<.009$). The difference between the amplitudes of the first and second harmonics (*H1-*H2) at all three locations in the vowels were also significantly higher for breathy vowels than for clear vowels ($t(9) = 7.22$-8.41; $p < .001$). Moreover, the *H1-A1 amplitudes were also significantly higher in breathy vowels than in clear vowels at 30% and 50% in the vowel ($t(9) = 4.64$, 3.31, $p < .001$, $.009$). The *H1-*A3 amplitudes at 70% in the vowel for breathy vowels were also found to be significantly greater than those of clear vowels ($t(9) = 4.30$, $p < .002$). These results suggest that the female speaker produced breathy vowels with a relatively greater amplitude, greater open quotient throughout the vowels, greater F1 bandwidth at the beginning and the middle of the vowel and a relatively greater spectral tilt toward the end of the vowel. Surprisingly, however, no difference in HNRs between breathy and clear vowels was found.

2. Male speaker

Similar to the female speaker, the male speaker's breathy vowels were produced with a relatively greater intensity than clear vowels (79.2 dB vs. 77.8 dB,

$t(9) = 3.77$, $p = .004$). The *H1-*H2 amplitudes of his breathy vowels at all three locations were also significantly greater than those of clear vowels ($t(9) = 6.51$, 3.42, 10.62, $p < .001$, .001, .008 respectively). *H1-A1 at 30% and 50% in the vowels were also significantly higher for breathy vowels than for clear vowels ($t(9) = 4.37$, 4.42, $p < .002$). Unlike the female speaker, however, the HNRs of breathy and clear vowels between 3,000 to 4,000 Hz, and between 4,000 to 5,000 Hz were significantly different ($t(9) = 2.78$, 4.42, $p < .021$, .002 respectively). The difference was, however, in an unexpected direction. That is, the HNRs of the clear vowels were lower than those of the breathy vowels. Thus, for the male speakers, acoustic characteristics of the breathy vowels include relatively greater intensity and greater open quotient. No difference between spectral tilts (*H1-*A3) between breathy and clear vowels was found.

3. Perception experiment

The goal of this experiment is to investigate whether or not the acoustic difference between breathy and clear voice quality in Chanthaburi Khmer can be perceived by listeners with phonetic training.

A. Stimuli

Two tokens of each of the five excised breathy and clear vowel pairs used in the acoustic analyses above were used in this experiment.

B. Listeners

Five native speakers of English (LM1, LF1-4) recruited from the graduate student population in the field of linguistics at Cornell University served as listeners for the experiment. All of these listeners had at least two courses of phonetics and are familiar with the breathy and clear voice distinction. All report normal speech and hearing.

C. Procedure

A total of 120 stimuli (2 phonation types x 5 vowels x 2 tokens x 3 randomizations x 2 speakers) were presented to listeners over headphones at a comfortable listening level. Stimuli were presented in a block of 12 tokens with an inter-trial interval of 2.5 sec. and inter-block interval of 5 sec. They were blocked by vowel and by speaker. Both vowel and speaker were counterbalanced. 10 practice trials (5 breathy and 5 clear vowels) were included. Thus, for each vowel pair, listeners heard 10 practice trials and 12 experiment trials.

All five listeners were given a printout with a scale of 1 to 7 for all 120 stimuli. A score of 1 indicated a fully clear voice quality and a score of 7 indicated a fully breathy voice quality. For each stimulus, the listeners were asked to give a score by circling a number ranging from 1 to 7 on the scale, depending on perceived degree of breathiness.

D. Results

1. Rating scores

The rating scores given by all five judges were averaged across repetitions for breathy and clear vowel pair for each speaker as shown in Tables 2 and 3. Paired-t-tests on the rating scores given to breathy and clear vowels were performed for each listener as well as across listeners. For the female speaker, across five judges, the breathy vowels received significantly higher rating scores than clear vowels (4.9 vs. 3.1, $t(4) = 2.78$; $p = .05$). However, even though breathy vowels received relatively higher rating scores than clear vowels from all listeners, the difference reached significance only in two out of five listeners, namely LM1 ($t\ (4) = 11.11$, $p = .01$ and LF1 ($t(4) = 3.65$, $p = .02$).

Table 2. Rating scores assigned by all 5 judges to breathy and clear vowel pairs spoken by the female speaker (F1). The averages across vowels and judges are given in bold.

Vowel	LM 1	LF 1	LF 2	LF 3	LF 4	X	Vowel	LM 1	LF 1	LF 2	LF 3	LF 4	X
ɛ̤	4.8	6.3	6.7	6.8	4.8	**5.9**	ɛ	1.8	2.3	1.8	2.3	2.2	**2.1**
i̤ə̤:	4.8	5.5	6.5	4.7	4.5	**5.2**	iɔ	2.5	2.3	1.0	2.0	2.8	**2.1**
ɔ̤o	5.7	6.2	1.0	5.0	4.7	**4.5**	ɔo	2.3	4.0	6.0	2.7	3.7	**3.7**
o̤u	4.5	4.3	6.7	1.8	4.2	**4.3**	ou	2.5	3.5	2.0	5.5	4.5	**3.6**
ə̤:	4.8	4.3	6.3	3.2	4.5	**4.6**	ə:	1.8	3.3	3.5	6.7	3.5	**3.8**
X	**4.9**	**5.3**	**5.4**	**4.3**	**4.5**	**4.9**	**X**	**2.2**	**3.1**	**2.9**	**3.8**	**3.3**	**3.1**

For the male speaker, even though the breathy vowels received slightly higher rating scores than clear vowels, the difference did not reach significance ($t(4) = .59$, $p = .587$,). This is true for both individual listeners as well as across listeners.

Table 3. Rating scores assigned by all 5 judges to breathy and clear vowel pairs spoken by the male speaker (M2). The averages across vowels and judges are given in bold.

Vowel	LM 1	LF 1	LF 2	LF 3	LF 4	X	Vowel	LM 1	LF 1	LF 2	LF 3	LF 4	X
ɛ̤	3.5	3.5	3.0	4.3	4.2	**3.7**	ɛ	4.2	3.5	2.7	1	5.5	**3.4**
i̤ə̤:	4.2	4.2	7	4.8	3.7	**4.8**	iə	2.3	3.3	1.0	1.2	4.3	**2.4**
ɔ̤o	3	3.3	3.7	3.3	2.3	**3.1**	ɔo	5.5	4.3	6.2	7	4.7	**5.5**
o̤u	5.5	4.2	6.7	3.8	4.8	**5.0**	ou	3.7	3.5	3.7	3.7	2.0	**3.3**
ə̤:	5	3.2	2	3.8	4.0	**3.6**	ə:	2.5	2.2	2.5	4.8	3.8	**3.2**
X	**4.2**	**3.7**	**4.5**	**4.0**	**3.8**	**4.0**	**X**	**3.6**	**3.4**	**3.2**	**3.5**	**4.1**	**3.6**

2. Multiple regression analyses

To examine which acoustic parameters accounted for the most variance in each listener's rating scores, a step-wise multiple regression analysis was performed between each listener's rating scores on all acoustic parameter measured. The results are shown in Table 4 for the female speaker and Table 5 for the male speaker.

Table 4. Results of stepwise multiple regression analyses for the female speaker. Only predictors which accounted for a significant portion of the rating scores are given. They were in the order shown.

Listeners	Acoustic parameters	Adjusted R2	F value	Signifi. F
LM1	*H1-*H2 at 30%	.43	15.07	.001
LF1	*H1-*H2 at 70%	.61	30.51	.001
LF2	HNR @60-1000 HZ	.20	5.64	.028
LF3	1. HNR @ 500-1000 Hz	.22	6.31	.021
	2. *H1-*A3 at 30%	.41	7.71	.004
LF4	HNR @ 500-1000 Hz	.36	11.91	.002

Results of the stepwise multiple regression analysis revealed that for the female speaker, the acoustic parameters that accounted for the variance in the rating scores of each judge were varied. For LM1, *H1-*H2 at 30% in the vowel accounted for 43% of the variance in his rating scores. For LF1, *H1-*H2 at 70% in the vowel accounted for most of the variance in her rating scores (61%). HNR at 60-1,000 Hz. was only the acoustic parameter that entered the equation for LF2 and accounted for 20% of the variance of her rating scores. HNR at 500-1,000 Hz accounted for more variance in LF3 and LF4's rating scores (22% and 36% respectively) than any acoustic parameters. *H1-*A3 at 30% also accounted for an additional 19% of the variance in LF3's rating scores.

Table 5. Results of stepwise multiple regression analyses for the male speaker. Only predictors which accounted for a significant portion of the rating scores are given. They were in the order shown.

Listeners	Acoustic parameters	Adjusted R^2	F value	Signifi. F
LM1	1. V. duration	.32	9.78	.005
	2. *H1-*A3 at 30%	.43	8.15	.003
LF1	1. V. duration	.18	5.17	.036
	2. *H1-*A3 at 70%	.34	5.82	.011
LF2	1. V. duration	.55	24.00	.001
	2. *H1-*H2 at 70%	.70	23.55	.001
LF3	*H1-*A3 at 50%	.29	8.91	.007
LF4	1. *H1-*A3 at 30%	.43	15.55	.001
	2 *H1-A1 at 50%	.55	12.71	.001
	3. V. duration	.68	14.66	.001

For the male speaker, vowel duration was the acoustic parameter that entered the equation and accounted for more variance in the rating scores of three out of five listeners. Specifically, it accounted for 32%, 18%, 55% and 13% of the variance in LM1, LF1, LF2 and LF4's rating scores (adjusted R^2 value). *H1-*A3 at 30% in the vowels also accounted for an additional 11% of the variance in LM1's rating scores and 43% of the variance in LF4's rating scores. *H1-*A3 at 70% in the vowel accounted for an additional 16% of the variance of LF1's rating scores. As for LF2, *H1-*H2 at 70% in the vowel was the acoustic parameter that accounted for an additional 15% of the variance in the rating scores. For LF4, besides vowel duration, *H1-*A3 at 30% in the vowel accounted for 43% of the variance in her rating scores and *H1-A1 at 50% in the vowel accounted for an additional 12% of the variance.

E. Discussion

Acoustic analyses revealed that both the male and the female speakers of Chanthaburi Khmer produced breathy vowels with a relatively greater intensity, open quotient (*H1-*H2) and F1 bandwidth (*H1-A1). Additionally, breathy vowels produced by the female speaker showed relatively greater spectral tilts (*H1-*A3) than those of clear vowels. These spectral characteristics of Chanthaburi breathy vowels are in agreement with breathy phonation found in other languages (e.g., Bickley 1982, Bali 1999).

One would expect that all of these spectral characteristics of breathy phonation in Chanthaburi Khmer would lead to a relative greater degree of noise or aperiodicity in the acoustic signal of a breathy voice thus a lower HNR. A lack of a significant difference in HNRs between breathy and clear vowels is rather surprising and no adequate explanation can be offered at this moment.

Results of the perception experiment showed that breathy vowels produced by the female speaker received significantly higher scores than clear vowels when averaged across listeners. For the male speaker, even though, on average, breathy vowels received higher scores than clear vowels, the difference did not reach significance. This is rather peculiar since according to the acoustic analyses, breathy and clear vowels for both speakers were successfully distinguished by vowel intensity, *H1-*H2 and *H1-A1. A careful examination of the results of the acoustic analyses reveals a possible explanation. As can be seen from Table 1, the magnitude of the difference between breathy and clear vowels in intensity, *H1-*H2 and *H1-A1 values was greater for the female speaker than for the male speaker. Take *H1-*H2 at 30% in the vowel for example, the difference between breathy and clear vowels for the female speaker is 5.62 dB, while that for the male speaker is only 4.16 dB. The difference in *H1-*H2 value at 50% in the vowel between breathy and clear vowels for the female speaker is 5.16 dB, while that for male speaker is 4.06 dB. This is true for all other acoustic parameters that differentiated between breathy and clear vowels for the two speakers. It is, therefore, not surprising that the female speaker was perceived to be more breathy than the male speaker. Results of stepwise multiple regression analyses also revealed that listeners relied mostly on vowel duration to differentiate between breathy and clear vowels produced by the male speaker. Taken together, results of the acoustic and perception analyses suggest that breathy phonation in Chanthaburi Khmer is disappearing from the speech of younger generations or that the breathy and clear phonation distinction preserved among older speakers is becoming a tense-lax distinction. This may be due to the influence of Thai which is the lingua-franca between the Khmer speakers and speakers of other languages in the region. The disappearance of breathiness in Chanthaburi Khmer may also be resulted from the low functional load of breathiness itself in the vowel system of Chanthaburi Khmer. As will be shown in the phonetic and phonemic analyses to be presented below, breathiness is only a subphonemic differentiation in most of the vowels in the vowel system of Chanthaburi Khmer.

II. Phonetic and phonemic analyses

1. Vowels

The goal of this experiment is to perform phonetic and phonemic analyses on the whole vowel system of Chanthaburi Khmer.

A. Stimuli

Stimuli used in this analysis consisted of 28 words with clear vowels and 25 words with breathy vowels (see the appendix). At least two repetitions of each word were used.

B. Subject

Since the acoustic and perceptual analyses just reported above indicated that only the female speaker retained the breathy and clear distinction that can be readily perceived by listeners, only her speech was chosen for the analyses.

C. Method

Recording of the stimuli was digitized on a SUN-Sparc station LX at 11 kHz at the Cornell Phonetics Laboratory. Each word was stored as a separate file to be processed by the commercial software package Entropics ESPS/ WAVE+. The beginning and end of the target vowel of each word were marked by examining both waveforms and wide-band spectrograms. Vowel onset was taken to be the onset of periodicity in the waveform. Vowel offset was indicated by the loss of the second formant (F2) on the spectrogram. Since the goal was to examine the quality of the vowels, the analysis focused on the first (F1) and second formants (F2). F1 and F2 measurements were taken from the middle of the vowels in the case of monophthongs, and from the middle of each element of diphthongs.

D. Results

Table 6 shows the mean values of F1 and F2 of both breathy and clear monophthongs of Chanthaburi Khmer. The data is presented in pairs of breathy and clear phonation, with long vowels followed by short vowels. This way of presentation makes it easier to see the breathy and clear correspondences of each orthographic vowel. The mean value given was averaged across repetitions for each vowel.

Table 6. Mean F1 and F2 values (in Hz) of Chanthaburi Khmer monophthongs.

Breathy				Clear			
Word	Vowel	F1	F2	Word	Vowel	F1	F2
ជឹក	[i̤ː]	255	2652				
ពឺ	[ɨ̤ː]	333	1460				
ពូត	[ṳː]	347	748				
ព្រេង	[e̤ː]	455	2483	ប្រេង	[eː]	477	2483
ពើប	[ə̤ː]	492	1450	ប៊ឺប	[əː]	520	1492
ជែក	[ɛ̤ː]	545	2433	កង៉ែប	[ɛː]	697	2101
គោក	[o̤ː]	516	975	កូប	[oː]	463	866
ពក	[ɔ̤ː]	645	1051	ក	[ɒː]	800	1277
				កកាយ	[aː]	978	1831
ខ្ជឹម	[i̤]	340	2520	ប៊ឹម	[ɛ]	520	2305
ទឹក	[ɨ̤]	426	2018	ប៊ឹត	[ə]	602	1473
ទិ ច	[ɪ̤]	399	2478	បិ ត	[e]	513	2329
				បិ ត	[ɒ]	777	1268
				ខឹង	[ɒ]	818	1267
ពុក	[ṳ]	378	878				
ជ័រ	[a̤]	762	1641				
ជិ ត	[ɨ̤]	404	1919	កិ ត	[ɛ]	538	2499
គាត់	[a̤]	702	1613	កាត់	[a]	820	1660
កំពប់	[o̤]	522	1165	កុដិ	[o]	588	1104
				កប់	[ɒ]	720	1274
គត់	[ɔ̤]	661	1271	សង្កត់	[ɒ]	850	1292
ជាក់	[a̤]	865	1786	ចាក់	[a]	886	1714

Table 7 shows mean across repetition of Chanthaburi Khmer diphthongs. Breathy diphthongs are presented first followed by clear diphthongs.

Table 7. Mean F1 and F2 values (in Hz) of Diphthongs.

		First element		Second element	
Breathy	Vowels	F1	F2	F1	F2
ព្រាប	[i̤ːᵋ]	365	2556	531	2115
ទៀន	[i̤ːᵋ]	326	2658	548	2149
ជឿ	[ɨ̤ːᶺ]	364	1587	508	1544
ទូត	[ṳːᶺ]	401	937	554	1284
ផ្ទៃ	[ɛ̤ᶦ]	535	2280	329	2551
ភ្លៅ	[ə̤ᵘ]	580	1336	428	882
Clear	Vowels	F1	F2	F1	F2
ត្រចៀក	[iːᵋ]	340	2784	571	2275
ប្រឿង	[ɨːᵊ]	478	1416	542	1453
ចូត	[uːᶺ]	414	1027	547	1304
កី	[ɛᶦ]	620	1943	341	2829
ផ្លូវ	[əᵘ]	557	1313	452	840
មុឺន	[əːᶤ]	566	1519	369	1518
ត្រី	[əːᶤ]	526	1577	378	1447
កោស	[ɔːᵒ]	713	1121	615	979
កើត	[aːᵊ]	768	1489	554	1496
កៃ	[aᶦ]	792	1983	436	2659
ចៅ	[aᵘ]	855	1626	510	880

Table 8 below shows 1st (clear voice) and 2nd (breathy voice) series of the Chanthaburi Khmer vowels. Long vowels are presented first, followed by short vowels and vowels occurring only in open syllables. Phonetic realization was based on the acoustic measurements shown in Tables 6 and 7. An attempt was made to approximate phonemic transcription as closely as possible to phonetic description. Examples of words on which the analysis was based are given in the last two columns. Breathy vowels are marked with [..] underneath and clear vowels are left unmarked.

Table 8. Phonetic realization and transcription of the Chanthaburi Khmer vowels.

1st and 2nd series realization of Chanthaburi Khmer orthographic vowels							
Symbols	Translitera-tion	Phonetic realization		Phonemic Transcription		Examples	
Long vowels		1st	2nd	1st	2nd	1st	2nd
1. _ី	i	ɛ^i	i̤ː	ɛy	i̤	កី	ជីក
		əː^ɨ		əɨ		ត្រី	
2. _ឺ	ɨ	əː^ɨ	ɨ̤ː	əɨ	ɨ̤ː	ម៉ឺន	ពឺ
		ə̤ː		əː		ប៉ឺប	
3. _ូ	u	oː	ṳː	oː	ṳː	កូប	ពូត
4. េ_	e	eː	e̤ː	eː	e̤ː	ប្រេង	ព្រេង
5. េ_ី	ə	aː^ə	ə̤ː	aə	ə̤ː	កើត	ពើប
6. េ_ា	o	ɔː^o	o̤ː	ɔo	o̤ː	កោស	គោក
7. ែ_	ɛ	ɛː	ɛ̤ː	ɛː	ɛ̤ː	កង្កែប	ជែក
8. _ា	a	aː	i̤ː^ɛ	aː	i̤a	កកាយ	ព្រាប
9. _	ɔ	ɒː	ɔ̤ː	ɒː	ɔ̤ː	ក	ពក
10. េ_ៀ	iə	iːɛ	i̤ː^ɛ	ia	i̤a	ត្រចៀក	ទៀន
11. េ_ឿ	ɨə	ɨː^ə	ɨ̤ːə	ɨə	ɨ̤ə	ប្រឿង	ជឿ
12. _ួ	uə	uː^ʌ	ṳː^ʌ	uə	ṳə	ចួត	ទួត
13. _័រ	ăr		a̤		a̤	–	ជ័រ

Symbols	Translitera-tion	Phonetic realization		Transcription		Examples	
Short vowels		1st	2nd	1st	2nd	1st	2nd
1. ិ	ĭ						
ិ F	ĭ + final	ɛ	ɨ̣	ɛ	ɨ̣	កិត	ជិត
		e	ɪ̣	e	ị	បិត	ទិច
		ɒ		ɒ		បិត	
2. ឹ	ɨ̆	ɒ	ɨ̣	ɒ	ɨ̣	ខឹង	ទឹក
			ị		ị		ខ្ទឹម
		e/ɛ		ɛ		ប៉ឹម	
		ə		ə		ប៉ឹត	
3. V	ŭ	o	ụ	o	ọ	កុដិ	ពុក
4. F	a + velar	a	ạ	a	ạ	ចាក់	ជាក់
	a + non-velar	a	ạ	a	ạ	កាត់	គាត់
5. L	ɔ + labial	ɒ	ọ	ɒ	ọ	កប់	កំពប់
F	ɔ + non-labial	ɒ	ɔ̣	ɒ	ɔ̣	សង្កត់	គត់
Vowels occurring only in open syllables							
1. ី	i	ɛi			ɛy	កី	
2. ូវ	uw	əu			əw	ផ្លូវ	
3. ែ	ai	ai	ɛ̣i	ay	ɛ̣y	កែ	ផ្លែ
4. ៅ	aw	au	ə̣u	aw	ə̣w	ចៅ	ភ្លៅ

E. Summary of Chanthaburi Khmer vowel system

The vowel system of Chanthaburi Khmer is summarized below. Breathy vowels are marked with the [̤], and the clear vowels are left unmarked.

From the current analysis, Chanthaburi Khmer vowel system consists of 13 long monophthongs, nine short monophthongs and nine diphthongs or gliding vowels, altogether 32 nuclei including [ɛi] which occurs only in open rimes. Among these, 16 are breathy vowels and 16 are clear vowels. All high vowels, both short and long, are breathy while mid and low vowels are both breathy and clear.

Long vowels			Short vowels		
i̤ː	ɨ̤ː	ṳː	i̤	ɨ̤	ṳ
eː e̤ː	ə̤ː	o̤ o̤ː	e ~ ɛ ~ ə		o o̤ ~ ɔ̤
ɛː ɛ̤ː		ɔ̤ː			
aː	ɒː		a a̤	ɒ	

Diphthongs

ia i̤a	ɨə ɨ̤ə	uə ṳə
əɨ ~ əː		aə ɔo

Correspondence with Standard Khmer spelling is shown below. First register vowels are to the left of the slash and second registers are to the right. As can be seen from these correspondences, with the exception of /eː/, /ɛː/, /aː/, first register and second register vowels can be distinguished based on their qualities (i.e., diphthongized vs. non-diphthongized.) Therefore, among these vowels breathy and clear phonations are merely sub-phonemic differentiation. For /eː/, /ɛː/, /a/, on the other hand, breathy and clear phonations are phonemically contrastive.

េ◌ៀ = (ia/i̤a)	◌ឿ = (ɨə /ɨ̤ə)	◌ួ = (uə/ṳə)
◌ី = (*/i̤ː)	◌ឺ =(əɨ ~ əː/ɨ̤ː)	◌ូ =(oː/ṳː)
េ◌ = (eː/e̤ː)	ើ◌ = (aə/ə̤ː)	◌ោ = (ɔo/o̤ː)
ែ◌ = (ɛː/ɛ̤ː)	◌ា = (aː/i̤ə)	◌ = (ɒː/ɔ̤ː)
(◌ិ) , ◌ឹ = (e~ɛ ~ ɒ, ɛ ~ ə ~ ɒ /i̤, ɨ̤)		◌ុ = (o/ṳ)
	◌◌់ = (ɒ/ɔ̤,o̤)	
	◌ា◌់ = (a/a̤)	

* = only in open rimes: ɛy ~ əːɨ

F. Discussion

Acoustic and perceptual investigation of Chanthaburi Khmer vowels confirmed the existence of the breathy and clear voice quality distinction at least in the speech of the older female speaker. Results of the perceptual investigation also suggested that this historical distinction is disappearing from the production of younger generation of Chanthaburi Khmer speakers. This may be due partly to the influence of Thai or the non-distinctive function of these two types of voice quality in most of the vowels in the system. For example, the phonemic analysis showed that breathy and clear phonations are phonemically distinctive only in mid front vowels /eː/ and low vowels (/ɛː/, /a/)[1]. Breathy and clear phonations are merely sub-phonemic differentiation in other vowels. In other words, except for the three non-high vowels, the two sub-systems (1^{st} and 2^{nd} registers) of Chanthaburi Khmer vowels can be completely differentiated by their qualities (diphthongized vs. non diphthongized).

It is interesting to point out that Chanthaburi Khmer has some features of a 'pure register' language, some transitional features and some 'restructured' language features according to Huffman's classifications (Huffman, 1976, 1985). For example, the sub-phonemic breathy and clear voice distinction in most vowels of Chanthaburi Khmer resembles one of the features of a 'transitional' language. The contrastive use of breathy and clear phonation among a few vowels (i.e., /eː/, /ɛː/ /a/), however, is a phonetic characteristic of a pure 'register' language. Further more, the complete merger of the proto Mon-Khmer voiced-voiceless contrast in Chanthaburi resembles a 'restructured' language.

However, since only vowels following stops were examined in this study whether or not the breathy and clear phonation in the vowel following continuants exists cannot be evaluated. These findings suggest that a complete differentiation between the four types of languages classified by Huffman may be arbitrary. This classification should be viewed instead as a continuum with phonetic features of a conservative language at one end of the continuum and features of a restructured language at the other. Languages may progress along the continuum and an overlap of features across language types may be expected in a particular language. Chanthaburi Khmer is one such example.

The confirmation of the existence of the breathy and clear phonations in Chanthaburi Khmer is crucial to the history of Khmer phonology. Specifically Chanthaburi Khmer provides evidence for an intermediate stage of the received theory of historical evolution of Khmer vowels (see Wayland 1997). In contrast to Huffman's (1976) observation, the existence of Chanthaburi Khmer and its preservation of the breathy and clear phonation distinction allows us to hypothesize that Khmer probably was a 'registered' language.

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[1] This is different from Diffloth's 1994 analysis. First register /eː/, /ɛː/ and /ɔː/ were transcribed as diphthongs /ɛe/, /aɛ/ and /ɔo/ respectively in his analysis. The discrepancy may be due to difference in words or speakers used in the two analyses.

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Appendix

កិ ត	[kɛt]	'to wipe'
បិ ត	[bɒt]	'to distill alcohol'
ខឹង	[kʰɒŋ]	'be angry'
បឺម	[bɛm]	'to suck (breast)'
ប៉ិ ត	[pət]	'to cut obliquely'
កុដិ	[kot]	'monk's living quarter'
ចាក់	[caʔ]	'to stab'
កាត់	[kat]	'to cut'
កប់	[kɒp]	'to bury'
សង្កត់	[sɒŋkɒt]	'to press down'
កី	[kɛi]	'a loom'
ផ្លូវ	[pʰlou]	'path, way'
កៃ	[kai]	'a trigger'
ចៅ	[cau]	'grandchild'
ម៉ឺន	[məɨn]	'ten thousand'
កូប	[koːp]	'a howdah'
កូត	[koːt]	'to play (a violin)'
ប្រេង	[preːŋ]	'oil'
កើត	[kaət]	'to originate'
កោស	[kɔoh]	'to scrape'
កង្កែប	[ŋkɛːp]	'a frog'
កកាយ	[kəkaːi]	'to scratch'
ក	[kɒː]	'neck'
ត្រចៀក	[təciɛʔ]	'ear'
ប្រឿង	[priəŋ]	'light (of color)'
ចួត	[cuət]	'to wrap around'
ត្រី	[trəɨ]	'fish'
ប៉ឺប	[pəːp]	'sound of a barking deer'
ជិ ត	[cɨ̤t]	'to be close'
ទិ ច	[ti̤c]	'to sting'
ខ្ទឹម	[kʰtɨ̤m]	'onion, garlic'
ពុក	[pṳk]	'to be rotten'
ជាក់	[ca̤ʔ]	'obvious'
គាត់	[ka̤t]	'he, she'
កំពប់	[kəmpo̤p]	'to spill'
គត់	[kɔ̤t]	'complete'
ថ្ទៃ	[pʰtɛ̤i]	'cloth bag'
ភ្លៅ	[pʰlo̤u]	'buttocks'
ជីក	[ci̤ːk]	'to dig'
ពី	[pɨ̤ː]	'dense, thick'
គឺ	[kɨ̤ː]	'to be'
ពូត	[pṳːt]	'to squeeze'
ព្រេង	[pre̤ːŋ]	'old'
គោក	[ko̤ːk]	'land'
ជែក	[cɛ̤ːk]	'to part hair'
ព្រាប	[pri̤ɛp]	'a dove'
ពក	[pɔ̤ːk]	'a bump'
ទៀន	[ti̤ɛn]	'candle'
ជឿ	[ci̤ə]	'to believe'
ទួត	[tṳət]	'g.g. grandfather'
ជ័រ	[ca̤r]	'resin'
ពើប	[pə̤ːp]	'to meet accidenta
ទឹក	[tɨ̤k]	'water'