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BRUCE MORÉN and ELIZABETH ZSIGA

THE LEXICAL AND POST-LEXICAL PHONOLOGY OF THAI TONES*

ABSTRACT. At first glance, the five-tone system of Thai looks quite simple. However, a detailed examination of the phonological distributions of segments and tones, combined with a careful analysis of the phonetic realizations of duration and pitch in both citation forms and connected speech, lead to the conclusion that the system is in fact complex and interesting. Based on data from an acoustic experiment, we claim that the tone bearing unit in Thai is the mora, and that previously unexplained restrictions on the distributions of tones in syllables closed by obstruents are the result of a relationship between the glottal feature and low tones. We describe and explain unexpected differences in the realization of tones in different phrasal positions in connected speech, and show that there are non-neutralizing contour tone simplifications that take place non-finally at the post-lexical level. Our analysis combines descriptive phonetics and phonology with both representational and constraint-based explanations (incorporating positional faithfulness and stratal Optimality Theory) to provide a unified account of the Thai tonal system. Our study supports a view of the grammar in which phonetics and phonology are separate, yet intricately related.

1. The Tones of Thai

1.1. *Introduction*

Standard Thai[1] contrasts five different tones. Linguists have traditionally (at least since Abramson 1962, following Pike 1948) described and transcribed these tones as mid, low, high, falling and rising. The five contrastive tones are shown in (1).

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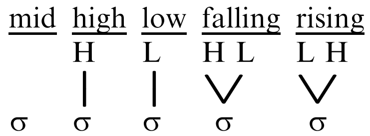
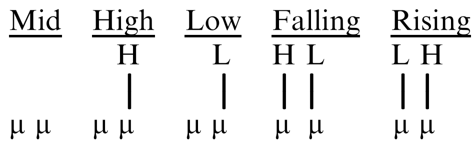
[1] We are concentrating on Standard Thai as spoken in Bangkok. Note that dialects of Thai are often distinguished via tone-morpheme correspondences and differences in the number of allowed tones. We look forward to investigating different Thai dialects to place this work within a larger dialectal study.

(1) [na:] 'rice field'
[nà:] 'custard apple'
[ná:] 'aunt'
[nâ:] 'face'
[nǎ:] 'thick'

Beginning with the earliest works on autosegmental representations (e.g., Woo 1969; Leben 1971, 1973; Gandour 1974a), it has been argued that primitives high (H) and low (L), associated with the vowel or syllable, can capture this five-way contrast simply and elegantly, as shown in (2).

(2)


A closer look at the distribution and realization of these five tones, however, reveals that the system is not as simple as it first appears. Not only is there an interesting restriction on the type of tone allowed on certain types of syllables, but the phonetic realization of the phonological tones is more complicated than implied by the labels and representations above, and the realization of some of the tones changes dramatically from citation form to connected speech. Further, there is ample evidence that the mora is the tone-bearing unit (TBU) in Thai, not the syllable as (2) suggests. In this paper, we will argue that the lexical tonal contrasts of Thai should in fact be represented as shown in (3).

(3)


The paper is organized as follows. The remainder of section 1 presents the problems to be solved: the facts regarding the restrictions on the distribution of lexical tones in Thai, as well as the facts of the phonetic realizations of those tones in both citation forms and connected speech. The result will be a picture of the Thai tonal system that raises many questions regarding interactions among tones, segments and prosodic representations, as well as lexical and post-lexical phonology.The remainder of the paper will address these questions and provide a congruent representational and constraint-based analysis based on a careful examination of the phonetics of timing and pitch.

Section 2 describes the experimental design and data analysis methodology. Section 3 establishes the basic facts of moraic structure in Thai and presents our findings regarding the phonetic duration of syllable rhymes and rhyme segments. This will set up the distribution of segments and moras within the syllable. Section 4 then turns to the phonetic implementation of lexical tones in citation forms. Having established the phonetic pattern, we provide the basic constraints and rankings to account for the core of Thai tonal phonology – the distribution of tones in open and sonorant-final syllables. Next, we provide an analysis of the odd distribution of tones in obstruent-final syllables. In Section 5, we discuss the phonetic realization of the five Thai tones in running speech and show that despite quite unexpected surface tonal contours (e.g., the falling tone does not fall), contrasts are recoverable from correspondences between the phonological representations and static perceptual cues. Using a combination of Stratal OT (Kiparsky 2000) and Positional Faithfulness (Beckman 1995), we not only model the difference in pronunciation between citation/phrase-final and non-final forms, but we also account for slight differences in post-lexical grammars between speakers. Finally, we close by highlighting the larger conclusions that can be draw from this study.

1.2. *Restricted Distribution of Lexical Tones*

Let us begin with a description of the restrictions on the distribution of lexical tone in this language. First, not all syllables can bear all tones. Only open syllables with long vowels (CVV), or any syllable closed by a sonorant consonant regardless of vowel length (CVS and CVVS), can bear all five tones. Open syllables with short vowels (CV) do not occur in stressed positions.
Examples are given in (4).[2]

(4)	CVV			CVS		CVVS	
	mid	[na:]	'rice field'	[laŋ]	'crate'	[la:ŋ]	'omen'
	low	[nà:]	'custard apple'	[làŋ]	'to flow'	[ŋà:ŋ]	'chime of bell'
	high	[ná:]	'aunt'	[lám]	'to go beyond'	[lá:ŋ]	'to wash'
	falling	[nâ:]	'face'	[lâm]	'sturdy'	[lâ:ŋ]	'below'
	rising	[nǎ:]	'thick'	[lǎŋ]	'back'	[lǎ:ŋ]	'grandchild'

[2] Although there was a connection between consonant laryngeal specification and corresponding adjacent vowel tone in Thai tonogenesis, that connection is largely historical in the synchronic grammer.This is amply illustrated by the minimal and near minimal pairs in (4).

On syllables closed by obstruents, the tonal distribution is restricted in an unexpected and puzzling way. On CVO syllables, only high and low tones can occur, and on CVVO syllables, only falling and low are allowed.[3] Examples are given in (5).

(5)

	CVO		CVVO	
mid	---		---	
low	[lạ̀k]	'stake'	[là:k]	'various'
high	[lák]	'to steal'	---	
falling	---		[lâ:k]	'to tow'
rising	---		---	

The absence of mid tone on obstruent-final syllables is a markedness paradox. If mid tone is the lack of a phonological tone specification and lack of tone is structurally less marked than the presence of tone (Yip 2002), or if tones in the middle of the pitch range are less marked than more extreme tones (as the issue was stated by Maddieson 1978), then why is a tone required on these syllables? The lack of high tone on CVVO is also a markedness paradox, since falling, a contour tone, should imply high, a simple tone (Maddieson 1978; Yip 2002). In addition, one must explain the absence of rising tone on CVVO and the lack of any contours at all on CVO.

These distributional gaps have been discussed in previous literature (Kruatrachue 1960; Abramson 1962; Gandour 1974a, 1974b, 1977; Yip 1982, 2002; Zhang 2002) and two different partial explanations have been proposed. Gandour (1974a, 1977) and Zhang (2002) impute the lack of rising tone on obstruent-final syllables to the relatively shorter duration of these syllables.These authors cite phonetic studies (Ohala and Ewan 1972; Sundberg 1973, 1979; Xu 1999a, 1999b) that have shown that rising contours may be articulatorily more difficult to implement than falling contours, and therefore tend to take longer. Gandour and Zhang thus argue that rising contours are prohibited on obstruent-final syllables in Thai because the relatively shorter duration of the sonorant portion of the rhyme does not allow sufficient time for a

[3] According to Gandour(1974a), the rare exceptions with CVVC-H(e.g. [k^há:t] 'card', [ó:t] 'buzz') and CVC-HL(e.g. [k^hlâk] 'crowded') are either loan words or onomatopoeia. Yip (1982) disputes this claim, but does not provide much data. We leave the analysis of these exceptions to future research. It must be noted, however, that the existence of these counterexamples does at least confirm that the constraints on the distribution of tones on obstruent-final syllables are phonological, not phonetic. The prohibited patterns are perfectly pronounceable; they are simply not normally good Thai.

rise to be phonetically realized. The markedness of rising contours, and their association with syllables of longer duration, finds some cross-linguistic and diachronic support. Typological surveys (Maddieson 1978; Yip 2002; Zhang 2002) have found that falling contours are more common and tend to occur on a wider variety of syllables than rising contours. Gandour (1977) reports that, in certain Northern and Southern dialects of Thai, there has been a loss of the vowel length distinction (even on sonorant- final syllables) dependent on tone class. Short vowels with rising tones became long, while long vowels with falling or level tones became short. An account based on duration, however, cannot account for the prohibition against mid tones, nor can it explain why high tones (which are in fact realized as a phonetically rising contour, as shown below) are prohibited on CVVO but allowed on CVO, the shortest syllables of all.

Yip (1982, 2002) grounds the prohibition against rising contours not in duration, but in glottalization. Following Abramson (1962), Yip notes that syllable-final obstruents in Thai are both voiceless and glottalized, and she formulates a negative constraint "*LH[+ glottal]", which prevents rising contours from associating with obstruent-final syllables. Yip (1982) proposes that this constraint is also active in the Burmese language Zahao. She does not, however, extend the analysis to account for other gaps in the Thai tonal system. Regarding the lack of mid tone on obstruent final syllables, Yip (1982:89) says, "the absence of M is odd, and neither Gandour nor I have any explanation to offer..." Yip (2002:203) reiterates "the absence of plain M and H on CVVC syllables in Thai remains a puzzle."

1.3. *Phonetic Realization of Tones in Citation Forms*

A further complication for Thai tones is the fact that the actual phonetic shapes of the individual tones, even in citation form, do not match the phonological labels mid, low, high, falling, and rising. Acoustic analyses of tonal shapes in citation forms include Abramson (1962), which is still considered the standard reference work; Erickson (1974); and Gandour et al. (1991). (Further acoustic studies of tones in connected speech are discussed below.) These sources are in general agreement as to the shapes of the five Thai tones (see Figure 4 p. 17).[4]

[4] A very early acoustic analysis, Bradley (1911), shows different shapes for the high and rising tones, but at this point in the discrepancy is probably irreconcilable: it is impossible to determine whether the differences are due to error, problems with recording device, dialectal differences, or diachronic change.

The only tone which is approximately level is the mid tone. The high tone actually rises (from the mid range to a high point at the end of the syllable) while the low tone actually falls (from mid to low). The falling tone is realized as a rise-fall contour, and the rising tone is realized as a fall-rise contour. Following Pike (1948), Abramson reserved the "dynamic" labels falling and rising for the two tones that had the greatest pitch excursions, and the "static" labels high, mid, and low for the tones with the smaller pitch excursions, while carefully noting that none of the tones were static in fact. Later perceptual testing with synthetic speech (Abramson 1975, 1978) found that Thai speakers were willing to identify level trajectories as high, mid, or low (with the tonal space about equally divided between the three), but that adding some pitch movement (up to a 30 Hz change over the course of the syllable) made the "level" tones less confusable and more acceptable to the listeners.

Abramson's (1962b) study was based on the speech of two older male speakers. Gandour et al. (1991) compared the citation productions of 20 different speakers, including older men and women, and younger men. This study largely confirmed the tonal contours reported in earlier work, but highlighted a number of points where variability can occur. Gandour et al. found that speakers varied in the extent of the initial rise on the falling tone, and that many speakers ended the high tone with a steep fall. (Other writers, e.g. Luksaneeyanawin (1983) and Kallayanamit (2004), have suggested that this optional final fall is intonational.) Speakers also varied as to the shape of the rise that characterizes the high tone: for some the trajectory was slightly convex (as reported by Abramson), but for others the trajectory was concave, or scooped. Interestingly, there were two speakers who combined these options in such a way that the contour shapes of the high and falling tones were nearly identical: an initial convex rise from mid to high, followed by a steep fall. The only difference between them was that the peak was reached earlier for the falling tone than for the high tone. Generalizing over all the variability found in their data, Gandour et al suggest that it is the *timing* of the peak in the tonal contour, not the shape of the contour itself, that is the primary cue for distinguishing these two tones: "the F0 contours of the falling and high tones ... appear to be distinguished primarily in terms of the location of the turning point" (p. 370).

These complex phonetic shapes, such that no tones are really level, and "high" and "falling" are distinguished not in that one is phonetically high and the other phonetically falling, but in whether their identical rise-fall contours have an early or late peak, pose a challenge to the simple Hand L associations proposed by autosegmental phonology. The complexity of attempting to map H and L auto-segments onto the actual contours of the tones of Thai leads Abramson (1979) to reject a compositional analysis of the contours. He argues (p. 7) that the acoustic and perceptual data "lend no phonetic plausibility" to arguments for the specification of rising and falling tones as sequences of H and L autosegments. "For phonetic support of the argument one would expect to be able to devise a formula by which the dynamic tones were obviously to be derived from the shape of the static tones. Even the citation forms, let alone the F0 curves of running speech, provide no acoustic basis for such a claim. It seems psychologically far more reasonable to suppose that the speaker of Thai stores a suitable tonal shape as part of his internal representation of each monosyllabic lexical item" (p. 7). While the phonological evidence for the compositionality of contour tones is overwhelming (Leben 1973; Gandour 1974a; Anderson 1978; Yip 1982, 1995, 2002; Duanmu 1994, etc.), the "formula" for the phonetic implementation of the tonal contours of Thai has not yet been devised. Phoneticians who pay careful attention to the trajectories of contour tones (e.g., Xu 1998) continue to suggest that the contour tones of Asian languages should be represented as whole tonal shapes rather than as a sequence of phonological levels.

1.4. *Phonetic Realization of Tones in Connected Speech*

The realization of tonal contours in connected speech complicates the picture even further. All sources agree that at least some of the tonal contours undergo significant changes from citation form to running speech. Sources disagree, however, over exactly what those changes are and when they occur. Gandour et al. (1999:124) note that "work on the production of Thai tones in connected speech is in its infancy.... A consensus has yet to emerge regarding the phonetic realization of Thai tones on unstressed syllables in connected speech.... We are still unable to tease apart effects on F0 contours due to speaking rate as opposed to those attributable to stress or sentence position." In this paper, we separate out and concentrate on the problem of variation in tonal shape due to position in the utterance, leaving the controversial question of tone patterns in unstressed syllables for future research. See Hiranburana (1971), Leben (1973), Luksaneeyanawin (1983), Potisuk et al. (1994, 1996), and Gandour et al. (1999) for data and discussion of tone in unstressed syllables in Thai. Several of these studies, as Gandour et al. (1999) note, do conflate stress and utterance position, comparing stressed final syllables with unstressed medial syllables, so that studying the effect of utterance position independent of stress should help clarify the question of the effect of stress as well.

Three previously published studies, Abramson (1979), Gandour et al. (1994) and Potisuk et al. (1997), have examined the realization of tonal contours on non-final, stressed syllables in connected speech. The focus of these studies was on tonal coarticulation rather than utterance position per se, but they provide important data on tonal patterns in connected speech. All three experiments used short, four-word utterances (though the utterances were not the same across studies), each word of which was designed to bear equal stress. Abramson (1979) and Gandour et al. (1994) examined all possible tone combinations (25) on the middle two words of the utterance; Potisuk et al. (1997) looked at all possible tone combinations (125) on the first three words. Abramson presents a partial data set from one male speaker, Gandour et al. present data from 10 male speakers (mean age 26), Potisuk et al. from three male and three female speakers (mean age 30). It is also worth noting that none of these studies explicitly varied syllable type. Abramson used all CVV syllables, while Gandour et al. used different syllable types for the different tones (e.g., CVS for falling and CVVO for low), a drawback that was noted and corrected in Potisuk et al., which used all CVV (second syllable) and CVVS (first and third syllables).

The three studies agree in their findings. There is no evidence of tone sandhi or neutralization of contrast in stressed syllables: regardless of the target tone or surrounding context, the five-way lexical contrast is maintained, and one tone never changes into another. The studies do find coarticulation, however, mostly perseverative. While all five tones remain distinct, tonal contours begin significantly higher when preceded by a high-toned syllable and significantly lower when preceded by a low-toned syllable. Interestingly, however, none of the studies found that target syllables began lower when preceded by a *falling* tone. Potisuk et al. report that rising tones caused a slightly higher onset on some following tones, but the effect was not consistent across speakers or contexts.

Why should high and low tones affect the following syllables in connected speech when rising and falling tones do not? The three studies agree in finding that the pitch excursion in the second half of the syllable, the actual fall of the falling tone and the rise of the rising tone, is curtailed. In citation forms (reported in other studies, as cited above) both low and falling tones end at the bottom of the pitch range, while both high and rising tones end at the top of the pitch range. In connected speech, however, rising and falling tones "most notably exhibit less extreme F0 offsets" (Potisuk et al. 1997:31), ending just in the middle of the pitch range, no higher or lower than mid tones. It is only the offsets of the contour tones that are reported to be affected: the early high peak of the falling tone and the high offset of the high tone remain at the top of the pitch range, and the early low point of the rising tone and low offset of the low tone remain at the bottom of the range. Thus, the "simple" high and low tones have significant coarticulatory effects on following syllables, while the mid, rising, and falling tones do not. The finding that syllables following contour tones begin no differently than syllables following mid tones indicates clearly that the high and low offsets of the contour tones are reduced in extent, not delayed in time.

The change in the offsets of the contour tones is seen to be greatest in the data of Potisuk et al. In the graphs of the data presented in that article, the "falling" tone, which is realized as rise-fall in citation forms, is often realized in connected speech as just a phonetic *rise*: rising from mid to high in the first half of the syllable, then leveling off or dropping just slightly in the second half. Examples of falling tones that do not fall and rising tones that do not rise from our own data are shown in Figures 1 and 2. (These data will be presented in greater detail in the sections to follow and are given here only as a demonstration of some of the complexity that requires an explanation.) Figure 1 (left) shows that in citation form or in phrase-final position, the falling tone is realized with a rise-fall contour. In non-final position in connected speech (Figure 1, right) there is no actual fall: the pitch rises during the first half of the syllable and then remains high. There is also variation in the realization of rising tones by different individuals. As shown in Figure 2, the non-final rising tone has a fall-rise contour for the speaker shown on the left, but for the speaker shown on the right the same token in the same environment is realized with falling pitch for most of the syllable duration, with a very slight upturn only at the end.

In summary, the phonetic data on the realization of Thai tonal contours in connected speech leave several questions unanswered

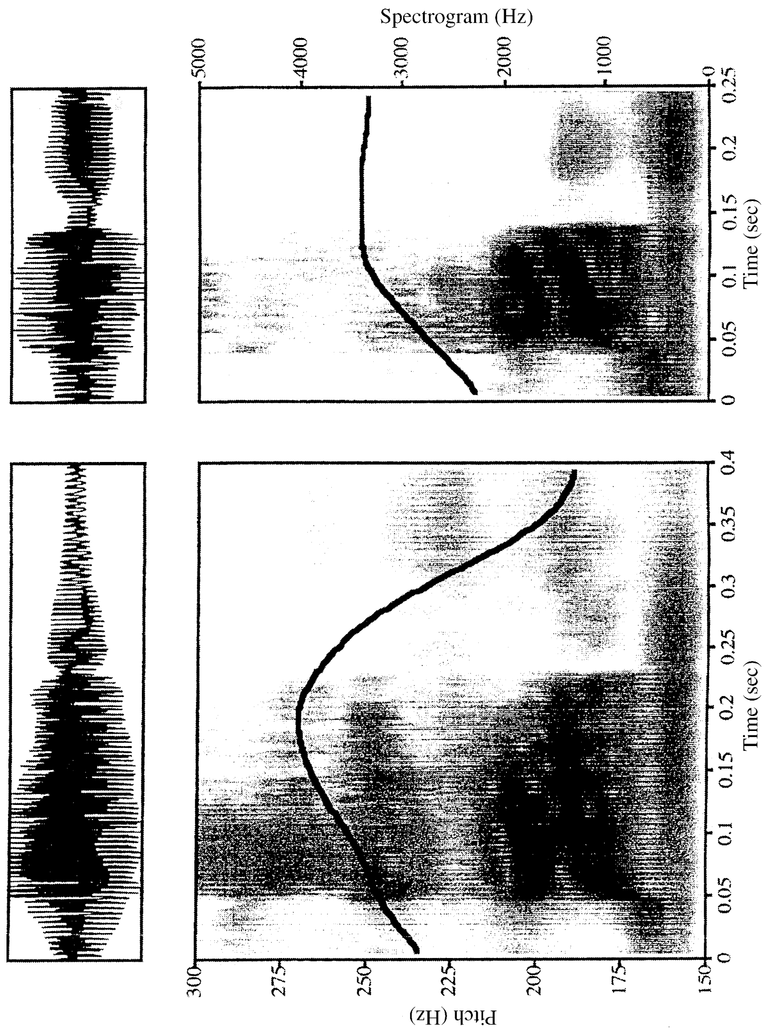


Figure 1. Falling tones have falling pitch in citation form, but not in connected speech. The syllable /lâm/ 'sturdy' produced by Speaker 1 in citation form (left) and in connected speech between two mid tones (right).

(apart from the problem of tone in unstressed syllables, which is not addressed here). To what extent are contour tones reduced or simplified in connected speech? Why is it specifically the second half of the contours that is targeted for reduction? How should such simplification without neutralization be represented? If "falling" tones can be realized with phonetically rising contours in connected speech

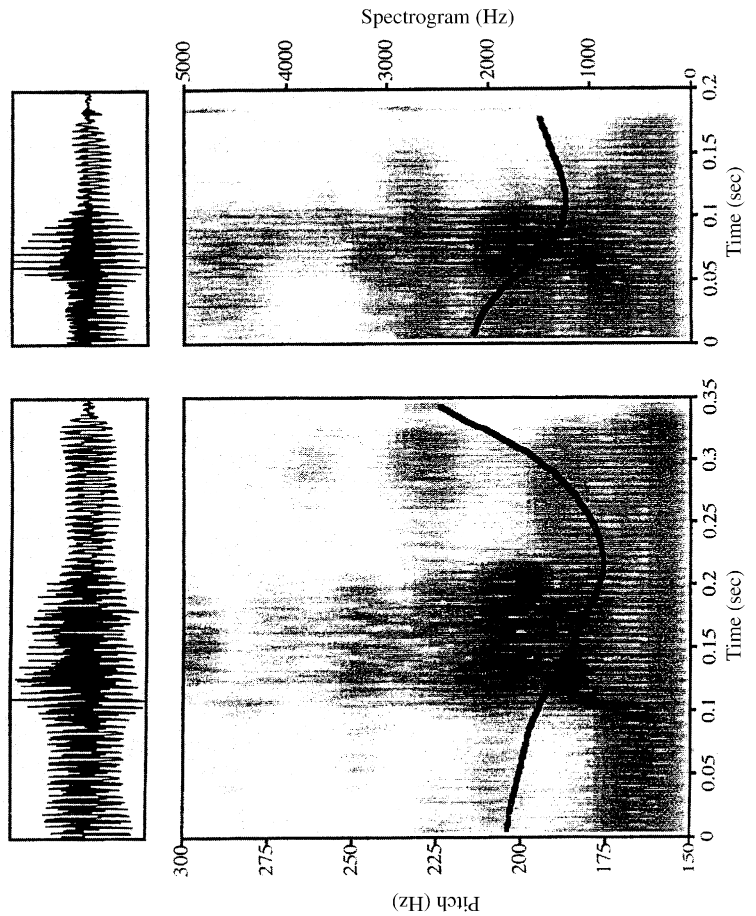


Figure 2. In connected speech, rising tones do not always rise. The syllable /lǎŋ/ 'back' produced in connected speech between two mid tones by Speaker 1 (left) and by Speaker 2 (right).

(and "high" tones can be realized as phonetically falling in citation forms), are there any stable points by which the tones can be consistently identified? If the speaker of Thai stores "a suitable tonal shape" for every lexical item, as Abramson (1979) suggested, what would that tonal shape be?

1.5. *What is the TBU in Thai?*

Each of the preceding problems – restricted lexical distributions, contours in citation forms, and simplifications in connected speech –

relates to how tones associate to larger units, and thus to the question of what prosodic entity is the tone-bearing unit (TBU) in Thai. Currently, there is much confusion and disagreement regarding the nature of the TBU when comparing languages. (See Odden 1995 and Yip 1995 for general discussion.) In the literature on TBUs in both Asian and African tone languages, the segment, the syllable and the mora have all been championed by one linguist or another depending on the specific language under investigation. For African languages, Clark (1990) has argued that tones are laryngeal features within the segment; Odden (1989), Clements (1986) and Pulleyblank (1994) among others have claimed that the mora is the TBU; and Odden (1990) and Clements (1984) among others have claimed that the syllable is the TBU. For Asian languages, Duanmu (1990, 1994) claims that the mora is the TBU and Yip (1995) claims that the syllable is the TBU. Yip (2002:74), after surveying many types of tone systems around the world, suggests, "Tone always associates to prosodic entities. Languages can differ in whether the syllable or the mora is the TBU." While we do not resolve this debate, we concur with Yip (2002) that tones may associate with different prosodic domains in different languages.

For Thai specifically, the vowel, syllable, and mora have each been suggested as the TBU. Early autosegmental accounts (Leben 1971, 1973; Gandour 1974a) proposed the vowel as the TBU. Phonetic studies (e.g., Abramson 1962; Potisuk et al. 1997; Xu 1998) and some later autosegmental accounts (Yip 1982; Zhang 2002) have generally assumed that Thai tones are the properties of syllables. Yip (2002:202-204) suggests that both the syllable and mora are candidates for the TBU in Thai. She first notes that Thai is a "syllable-toned language," but then argues that the prohibition against contours on CVO syllables is "reminiscent of Cantonese... for which I proposed that the TBU was the mora." On the other hand, Yip points out that other restrictions on tonal associations, such as the lack of high, mid, and rising on CVVO remain unexplained, and points out that "the simple *number* of TBUs is not going to help here." The question of what entity serves as the TBU in Thai thus has remained unresolved.

In this paper, it will be argued that the mora is the TBU in Thai, and that the five-way tonal contrast should be represented as was shown in (3). The rest of the paper will present the evidence for this representation. Based on data from an acoustic experiment, and building from the proposition that tones are associated to moras rather than to syllables, we will suggest how the problems presented above can be solved. Our analysis will account for the unexpected realizations of falling and rising tones in connected speech, as well as the phonetic timing of tonal contours in both citation form and connected speech. We provide a unified account of several related phonological phenomena, including the two markedness paradoxes, using very simple tools of analysis that are based in, but separate from, phonetics.

2. Experimental Design

In order to further investigate the phonetic realization of tonal contours in Thai, we recorded two female speakers of the Bangkok dialect, both in their late twenties and both graduate students at Georgetown University at the time of the study. The study was designed to compare the realization of tonal contours in citation form and in connected speech, while holding stress constant. By comparing the timing of pitch trajectories on different syllable types, the relationship between pitch targets and moraic structure can be evaluated. The present study adds to the findings of earlier experiments by explicitly comparing citation and connected speech realizations from the same speakers, using longer utterances, introducing controlled variation in syllable type, and in focusing on the speech of young, urban females.

Each speaker recorded a total of 12 repetitions of each of the words in (4) and (5), which represent all possible occurring combinations of stressed syllable type and tonal contour. All target syllables bore the main (contrastive) stress of the utterance. The segmental material was controlled for to the greatest extent possible – all target syllables contain the same vowel and begin with a sonorant, and closed syllables end in either a nasal or a velar stop.

Three repetitions were recorded for each of the following four contexts:

- Citation: in isolation, preceded and followed by a pause;
- m_m: in a carrier phrase, preceded and followed by a mid-toned syllable;

/níd	bɔ̀k	na:	____	k^hɯ:	kamtɔ̀p/
N.	tell	N.	____	be	answer

Nid told Naa that ____ was the answer.

- h_h: in a carrier phrase, preceded and followed by a high-toned syllable;

  /níd bɔ̀k ná: ——— lɛ́ʔ lam kʰɯ: kamtɔ̀p/
  N. tell aunt ——— and stalk be answer
  Nid told her aunt that ——— and "stalk"were the answers.

- l_l: in a carrier phrase, preceded and followed by a low-toned syllable.

  /tɤ:m kam naɪ cç̧ɔ̂ŋwâ:ŋ ráwà:ŋ ——— kàp náp/
  fill word in blank between ——— and count
  Fill in the blank between ——— and "count".

For presentation to the speakers, all materials were written in Thai script. The different contexts were recorded in separate blocks, further ensuring that the target word would receive stress, but sentences were randomized within the blocks.

The recordings were digitized and analyzed using the Praat signal analysis program for the Macintosh. Pitch tracks for each syllable were made via an autocorrelation algorithm (Boersma 1993), using a 30 ms Hanning window with a step size of 5 ms. (Contours were subsequently smoothed within a 10 Hz bandwidth for graphing.) The duration of the vowel and coda consonant in each syllable was measured, and averages were computed for each syllable type. Since coda consonants are unreleased, coda duration in the obstruent-final syllables could only be measured in the h_h context, where the obstruent coda was followed by a sonorant onset.

In order to investigate the relationship between tonal contours and moraic structure, pitch values were measured in two different ways. In a first pass through the data, pitch values were measured at three points in each syllable: at vowel onset, at the end of the first mora (defined as the boundary between V and S for the CVS syllables, otherwise as the point halfway through the rhyme duration), and at the end of the sonorant portion of the rhyme. From those measures, the pitch change over the first and second moras was computed. In order to confirm the relevance of these measurement points, in an independent pass through the data, Praat's peak-picking algorithm was used to find the mid-syllable inflection point for each syllable bearing a high, falling, or rising tone (no mid-syllable inflection is expected for mid and low tones). The time points and pitch values found by the two different analyses were then compared.

3. Evidence for Moraic Structure in Thai

Before discussing the pitch findings of the experiment and relating those findings to our representational and constraint-based analyses of Thai tones, it is crucial to first establish the basic duration and weight description since we will claim that the TBU in Thai is the mora. These duration and weight facts lead to a straightforward analysis of the tonal system.

In Thai, long and short vowels are contrastive, but there are no extra-long vowels. That is, vowels may be mono-moraic or bi-moraic, but not tri-moraic. For example the words for 'crate' and 'omen' are differentiated only by vowel length ([laŋ] 'crate' vs. [la:ŋ] 'omen') as are the words for 'stake' and 'various' ([làk] 'stake' vs. [là:k] 'various').

Open syllables with short vowels occur only in unstressed positions, so we assume that all stressed syllables in Thai are bimoraic. Since closed syllables containing short vowels can bear stress, this indicates that the final consonants in Thai are moraic. Underlyingly short open syllables that occur in stressed position (the final syllable of the word) are made heavy by the addition of a final glottal stop. For example, the Thai word for 'state' is pronounced [rátt^{h}àʔ] in isolation, but with no glottal stop when the morpheme is the first member of a compound: [rátt^{h}àsàat] 'political science' (example from Gandour 1974b). The facts that (1) the glottal stop is not present when this class of morphemes is in non-head position in the foot and (2) stressed syllables containing short vowels and no coda do not occur on the surface, lead to the conclusion that the glottal stop is predictable and thus not underlyingly specified. Note, however, that an underlying glottal stop would behave identically to an epenthetic glottal stop with respect to both weight and tone.[5]

We claim that codas following long vowels share the second mora with the vowel. Therefore, CVVC syllables are not superheavy (tri-moraic).[6] The phonetic evidence directly supports this mora-sharing

[5] Gandour (1974b) in fact argues that final glottal stops must be underlying rather than epenthetic, despite their predictable distribution, based on the observation that CVʔ syllables obey the same morpheme structure constraints (no mid, falling or rising tones) that other obstruent-final syllables obey. Therefore, he argues, the glottal stops must be present in underlying representation, at the time he assumes MSC's are enforced, and then deleted in unstressed syllables, rather than absent at UR and inserted derivationally. In a theory in which all constraints are evaluated at the surface level, however, this objection disappears.

[6] Bennett (1994:40) makes similar claims.

claim. Mean durations of the vowel and coda consonant for each syllable type (averaging across tones) for each speaker are graphed in Figure 3. Phonetic shortening of long vowels in closed syllables, as well as shortening of coda consonants following long vowels, was evident. Following Broselow et al. (1997) we take this closed-syllable shortening as evidence that the coda consonant shares the second mora with the long vowel. We will see in section 4.4 that the tonal evidence from CVVO syllables further supports the conclusion of mora-sharing.

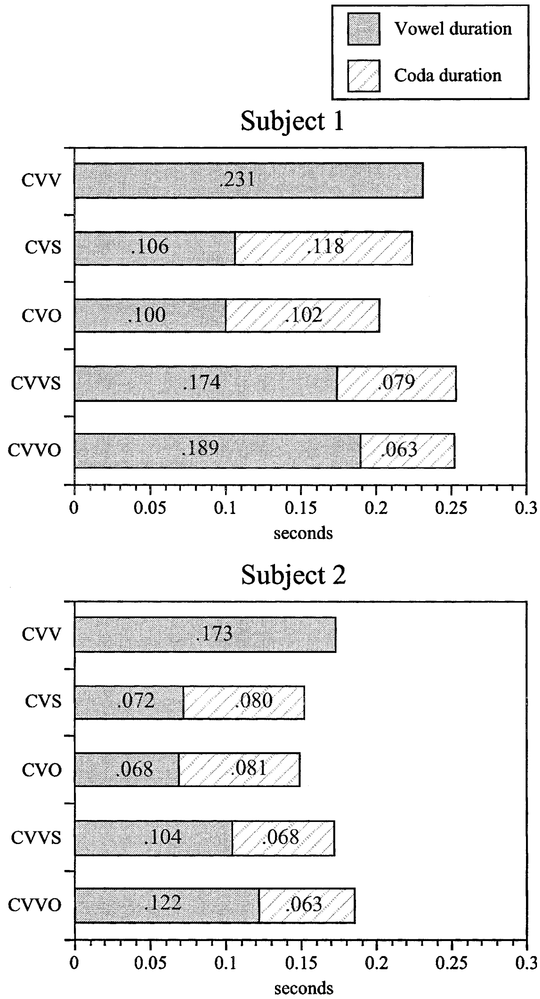


Figure 3. Mean durations of the nucleus and coda in different syllable types in connected speech.

Also worth noting is the consistent duration of each mora, particularly the near-equivalence of the duration of vowel and coda in CVS syllables. For Speaker 1, at her normal speaking rate, one mora was equivalent to 115 ms ($\pm$15 ms). Speaker 2 spoke considerably faster (one mora = 85 ms, $\pm$15 ms) but with the same consistency. While one can not make definitive claims of isochrony based on a study that did not systematically vary speaking rate, the duration data reported here suggest that the mora is the timing unit, as well as the tone-bearing unit, in Thai.

Having established how moras are relevant to this language, we can now address the issue of tonal affiliations within the syllable.

4. Tone Associations in Citation Forms

4.1. *Phonetic Data*

Exemplar pitch contours for the five contrastive tones in citation form for both speakers are shown in Figure 4. Pitch contours begin with the release of the onset consonant, and the falling and rising tones are shown with dashed lines. Each example depicts a single token: the second repetition of the CVVS, CVS, CVVO and CVO syllables. Each token graphed is representative of average F0 patterns, and is thus indicative of typical pitch contours for each condition. (Contours in the CVV syllables were identical to those in CVS, so are not shown. Recall that only falling and low tones occur on CVVO syllables, and only high and low on CVO.) The generality of the example patterns shown in Figure 4 is confirmed in Table I, which gives mean pitch values at salient points in the tonal contours, and mean pitch change in each mora, averaged for each speaker over all tokens of the citation form CVV, CVVS, and CVS syllables ($n = 9$).We will come back to a discussion of the pitch contours in connected speech in section 5.

In describing the pitch contours, it is useful to divide the frequency scale for our speakers into three sub-ranges (following Abramson 1978 and Erickson 1976): high (240–280 Hz), mid (200–240 Hz) and low (l60–200 Hz). In these descriptions, we abstract away momentarily from the up- and down-turns at the very ends of some of the contours, which we take to be intonational, and discuss below. Figure 4 illustrates the following:

TABLE I

Mean pitch targets (in HZ) at salient points in the citation form tonal contours, and mean pitch change over each mora, averaging over all CVV, CVS, and CVVS syllables ($n = 9$) for each speaker

	Pitch at vowel onset	Pitch at end of μ1	Pitch at end of μ2	Pitch change over μ1	Pitch change over μ2
S1					
Falling	252	262	183	10	−79
Rising	206	177	237	−28	60
High	218	212	250	−6	38
Mid	225	216	205	−9	−12
Low	203	182	173	−20	−9
S2					
Falling	245	261	178	15	−83
Rising	208	175	233	−32	58
High	227	213	251	−14	38
Mid	228	211	206	−17	−5
Low	208	182	166	−27	−15

- The falling tone is the only one that begins in the high range. It starts with a rising high during the first mora, and then falls steeply to the low range during the second mora.
- The rising tone begins in the mid range. It falls quickly and stays low during the first mora, then rises during the second mora, ending in the mid range. Note that although it does not reach the target range for high, the end of this tone does consistently exceed the end frequency of the mid tone.
- The low tone begins in the mid range and falls smoothly and steadily, reaching its lowest point at the bottom of the range at the very end of the syllable.
- The mid tone stays level or falls gradually through the mid range.
- The high tone stays level or falls slightly in the mid range through the first mora, then rises to reach the high range only at the very end of the syllable.
- In CVO syllables, where only a single sonorant moraic segment is available to realize the tonal contour, the pitch excursion is shorter and smaller than in the other contexts, but the high and low tones follow the same general pattern as for the other syllable types, the high scooping upwards and the low falling steadily.

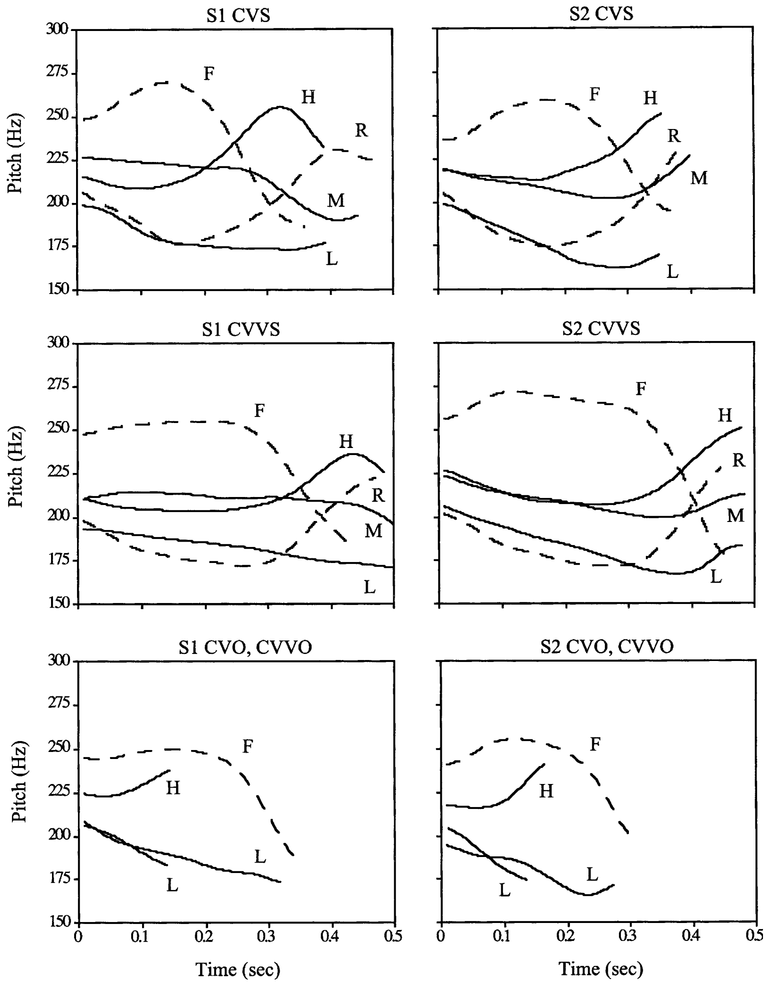


Figure 4. Exemplar pitch contours (1 representative token) for the five contrastive tones in citation form. Speaker 1, left; Speaker 2, right.

Note, in particular, that the "rising" tone is realized as a fall-rise, which ends in the mid range rather than at the top of the scale, the "falling" tone is realized as a rise-fall, and the "high" tone is as low as or lower than the "mid" tone for at least half of its duration. These contours are consistent with those reported for citation forms in the Bangkok dialect by Abramson (1962) and Gandour et al. (1991), with the provision that both our speakers used the "scooped" variant of the high tone reported by Gandour et al.

Note also that for the citation forms there is very little variation in tonal shape between syllable types, though predictable variation in duration is evident. CVO tokens are the shortest and CVVS are the longest. Between speakers, the only noticeable and consistent variability is in the way some of the contours end. For speaker 1, the high, rising and mid tones usually terminate in a slight fall, while for speaker 2 the low and mid tones terminate in a slight rise. (Optional final falls on high tones were also reported by Gandour et al. 1991.) Following Kallayanamit (2004) and Luksaneeyanawin (1983) we attribute these differences to intonational effects. For speaker 1, who spoke more slowly and deliberately, all citation tones end in a fall, indicating the end of the declarative utterance. For speaker 2, who spoke more quickly, the tones graphed here, which were the second in a series of three, end in a continuation rise. We abstract away from these intonational endings in our description and analysis. Interestingly, though our two speakers were of rather different height and weight, their pitch ranges were nearly identical.

4.2. *Moraic Alignment and Proposed Representations*

The inflection points in the tonal contours correspond very closely with the right edges of moras. This alignment was clearly seen in Figures 1 and 2 above (p. 10 and 11). The falling tone (Figure 1), and the rising tone (Figure 2) have an inflection point just at the end of the vocalic mora. In Figure 5 the alignment of a high tone contour to the segmental string is illustrated. It can be seen that the high tone turns upward just as the nasal consonant begins and reaches a peak high at the very end of the nasal consonant. The tonal alignment with the moraic structure was consistent across syllable types and between the two speakers.

Previous studies (Potisuk et al. 1997; Gandour et al. 1999) have noted that the falling, rising, and high tones change abruptly in slope "about halfway" through their duration, but the authors do not explicitly relate this timing to moraic structure.[7] In the data presented here, mid-syllable inflection points occurred nearly exactly at the end of the first mora. This claim of alignment was tested directly for all falling, rising, and high tones on sonorant-final syllables in both citation form and connected speech (a total of 108 tokens per speaker), by comparing the time of the pitch inflection point (as

[7] Gandour et al. (1991) report inflection points for the falling and rising tones occurring earlier, at about 30% to 40% of the duration of the contour (based on the data presented in their Figures 2–5 and Table II). These syllables all began with an aspirated consonant, however, so that the voiceless initial portion of the vowel, where pitch could be measured, was not included in the calculation.

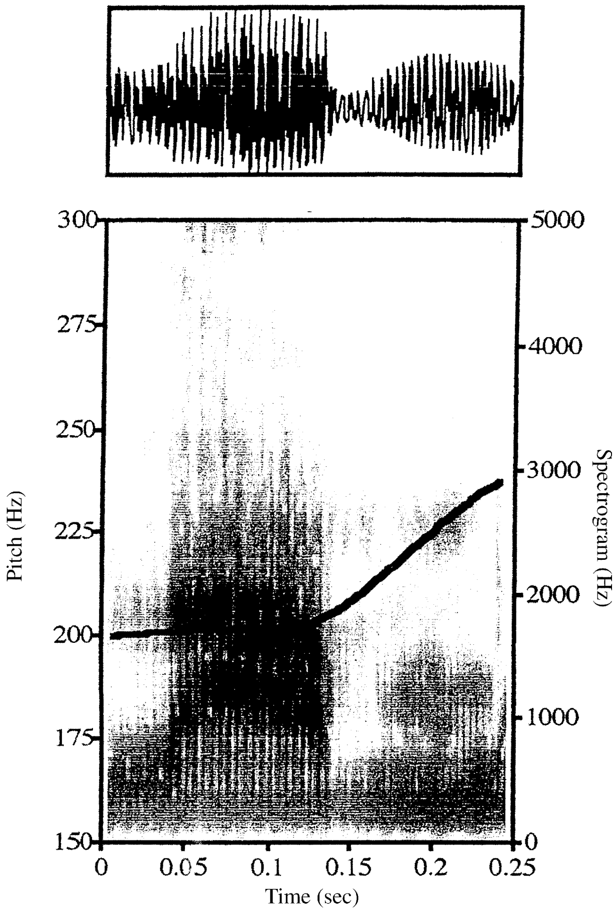


Figure 5. The high tone is realized as a scooped contour. The syllable /lám/ "to go beyond" produced by Speaker 1 in connected speech between two mid tones.

selected by Praat's automatic peak-picking algorithm) to the end-point of the first mora (defined as the boundary between vowel and consonant for the CVS syllables and the midpoint of the rhyme for CVV and CVVS syllables).[8] For speaker 1, the inflection point occurred, on average, 2.4 ms. before the midpoint of the rhyme (std. dev. 4.1 ms), and for speaker 2, the inflection point occurred on average just 0.2 ms after the midpoint of the rhyme (std. dev. 2.7 ms).Tokens where the two points differed by more than a few milliseconds (as in the CVVS tokens of speaker 2 in Figure 4) had a

[8] A slightly different alignment is proposed for obstruent-final syllables, as discussed below.

gradual turn in the pitch track rather than a sharp elbow, so that the mean difference in Hz between the two measurement points was only 2.3 Hz (std. dev. 2.7 Hz) for speaker 1 and 4.3 Hz (std. dev. 5.4 Hz) for speaker 2. We conclude that, in Thai, pitch contours are aligned with moraic structure.

If we assume that tones are associated to moras, the seemingly complicated citation pitch contours graphed in Figure 4 can be seen to correspond in straightforward fashion to phonological tone specifications. Our proposed phonological representations are repeated in (6). Syllables with "mid tones" have no phonological tonal specifications, thus they maintain neutral, slightly falling, pitch throughout their duration. "High tones," which remain in the neutral range through the first half of the syllable and reach a high point only at the very end of the rhyme, begin with no tone on the first mora and end with a high tone on the second. "Low tones," conversely, begin with no tone and end with a low tone on the second mora. The pitch contours for the "falling" and "rising" tones, which begin with definite movements up or down out of the mid range early in the syllable, undergo a change in direction midway through, and then reach a pitch extrema at the end of the rhyme, suggest that both moras are specified for tone. "Falling tones" begin with a high tone on the first mora and end with a low tone on the second mora. "Rising tones" begin with a low tone on the first mora and end with a high tone on the second mora.

(6)	Mid	High	Low	Falling	Rising
		H	L	H L	L H
		|	|	| |	| |
	μ μ	μ μ	μ μ	μ μ	μ μ

All of the phonological tones are aligned as far right in the syllable as possible, while still maintaining association with the appropriate mora (e.g., the peak high of the falling tone is reached at the right edge of the first mora). Such phonetic alignment is consistent with the literature on tonal and intonational modeling, in which pitch targets associated in the phonology to prosodic entities, usually the syllable, are aligned in the phonetics with the right or left edge of those entities (e.g., Bruce Garding 1978; Silverman and Pierrehumbert 1990; Prieto et al. 1995; Hermes 1997; Arvaniti et al. 1998; Xu 1998, 1999a, 1999b; Ladd et al. 1999, 2000).

Crucial to our analysis is the assumption that phonologically toneless moras are phonetically mapped to the neutral/default pitch range, with gradually falling pitch during the unspecified span. This assumption is consistent with the electromyographic (EMG) data on Thai tones collected by Erickson (1976, 1994). Erickson found that, for pitch raising, contraction of the cricothyroid muscle was necessary. For pitch lowering, however, muscle contraction (of the strap muscles) was found only for pitch drops to the bottom of the pitch range. For more gradual pitch lowering, either from high to mid or within the mid range, only *relaxation* of the cricothyroid was required. Based on Erickson's findings, we will assume that there is an active lowering gesture, and thus a phonological L specification, only on moras during which pitch drops to the low range, not on moras during which pitch drops gradually to or within the mid range.

Moraic alignment thus provides the explicit phonology to phonetics mapping called for by Abramson (1979). During phonologically unspecified moras (the whole of the mid tone, and the first moras of the high and low tones) there is a gradual pitch fall. For phonologically specified moras (each mora of the falling and rising tones, and the second moras of the high and low tones) pitch targets are aligned at the right edge of the specified mora. Thus the simple H and L auto segments required by the phonology map in straightforward fashion to the seemingly complex contours of the phonetics. As we will show, these tonal alignments are crucial in explaining both the phonetic realizations and the phonological patterns.

4.3. *Phonological Analysis of Tones in CVV, CVS and CVVS Syllables*

Given the phonetic facts of the tonal contours in citation forms, we now turn to the OT analysis of tonal patterns in CVV, CVS and CVVS syllables, establishing the constraint rankings that give rise to these lexical representations. All five contrastive tones are permitted in these syllables, as we just saw. We will only demonstrate our analysis using CVV syllables since it carries forward to all syllables closed by a sonorant.

Since there are many languages that do not have lexical tone, there must be a set of structural markedness constraints against tones. Following the lead of Prince and Smolensky's (1993) work on nontonal features, and the tonal work of others (e.g. Bickmore 1996; Zoll 1996; Yip 2002), we assume a constraint like that in (7).

(7) *[T]: Do not have a tone.

However, lexical tones are allowed in some languages, therefore there must also be a set of faithfulness constraints allowing them to surface if underlyingly specified. Following the Correspondence Theory view of faithfulness (McCarthy and Prince 1995), and the tonal work of Bickmore (1996) and Zoll (1996), we assume the constraint in (8).

(8) MAX[T]: Every tone in the input has a correspondent in the output.

Since we will see later that high and low tones are treated slightly differently in the phonology of Thai, the tonal constraints must be relativized to H and L. To ensure that both high and low tones are allowed in this language, the faithfulness constraints MAX[H] and MAX[L] outrank the markedness constraint *[H] and *[L], as shown in (9) and (10).[9]

(9) Contrastive high tone in citation CVV

	/na:-H/ 'aunt'	MAX[H]	*[H]
a.	na:	*!	
☞ b.	ná:		*

(10) Contrastive low tone in citation CVV

	/na:-L/ 'custard apple'	MAX[L]	*[L]
a.	na:	*!	
☞ b.	nà:		*

Falling and rising tones are also possible, therefore the faithfulness constraints on each simple tone must outrank a markedness constraint against having two tones per syllable.

(11) *[TT]σ - two tones within the same syllable domain are prohibited

(12) Contrastive falling tone in citation CVV

	/na:-HL/ 'face'	MAX[H]	MAX[L]	*[TT]σ
a.	na:	*!	*!	
b.	ná:		*!	
c.	nà:	*!		
☞ d.	nâ:			*

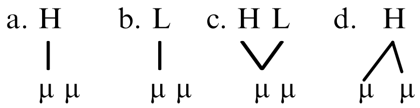
[9] In order to save space in the tableaux in cases where alignment is not a crucial issue, input tones are shown next to their associated lexical items in the input, and are transcribed with diacritics in the output candidates. Specific moraic associations are shown when necessary to make the point.

(13) Contrastive rising tone in citation CVV

	/na:-LH/ 'thick'	MAX[H]	MAX[L]	*[TT]σ
a.	na:	*!	*!	
b.	ná:		*!	
c.	nà:	*!		
☞ d.	nǎ:			*

The constraint rankings above allow the five lexically contrastive tones to surface on each sonorant-final syllable. We now turn to constraining the associations between tones and TBUs. As discussed by Yip (1995) and Odden (1995), one drawback to assuming the mora as the TBU is that, in principle, more tonal contrasts can be represented than the five that are possible if H and L (or Ø) are associated to the syllable, as in (2) above. For Thai, representations such as those in (14), where a single tone is associated to the leftmost mora of a syllable, where two tones share a single mora, or where two moras share a single tone, must be prevented from surfacing as lexically contrastive outputs.

(14) Non-occurring lexical tone associations in Thai



In much of the previous literature on tonal contrasts, it has been assumed that the only way to rule out contrasts such as those in (14) is to prevent the phonology from representing them. As Odden (1995:450) puts it: "Yet no language has more than one type of contour tone. Linking tones to syllables, not moras within the syllable, solves this problem.... In the syllabic TBU theory, there simply is no way to phonologically manipulate the realization of tones relative to the moras of a syllable." Yip (1995:489) argues: "If the mora is the TBU, a contour tone could be associated to each mora, giving highly complex tones such as rise–rise, which are not found, so it is not only possible but essential that the syllable be the TBU in Chinese." In constraint-based theories, however, the representations themselves do not have to bear the entire burden of limiting possible contrasts and alternations. (See, e.g., Padgett 2002, who argues that constraints on feature classes should replace the representational solution of feature-geometric class nodes.) There is thus greater freedom to choose the representation that most simply represents the phonological patterning and phonetic implementation of the language under study.[10]

The rest of this section presents the constraints on tonal alignment that allow all and only the five contrastive tones (shown in (2)) to surface in sonorant-final citation forms in Thai. We assume Richness of the Base (Prince and Smolensky 1993), so that all possible tonal combinations, including those in (14), are allowed as inputs, but only a select subset surface as optimal outputs. We will argue later in the paper, however, that a single tone linked to two moras, as in (14d), may surface as optimal under the special conditions imposed by short-vowelled, obstruent-final CVC syllables, and that single high and low tones associated to the first mora of the syllable (as in 14a, b) may surface as outputs of the post-lexical phonology in connected speech.

The phonetic realization of the simple tones suggests that they are aligned as far right in the syllable as possible, that is, on the second mora. Therefore, there must be a constraint (15) aligning a tone to the right edge of the syllable, which is ranked above a constraint aligning a tone to the left edge of the syllable, and also above a faithfulness constraint preserving any underlying tone-mora alignment (17). This is demonstrated in (18) and (19).

(15) ALIGN(Tone, Edge, Domain, Edge): align the tone at the X edge of the domain (following Generalized Alignment of McCarthy and Prince (1993), and implemented for tones at the right and left edges of a variety of domains in Kisseberth (1993), Lorentz (1995), Tranel (1995), Bickmore (1996), Zoll (1996), Yip (2002), etc.)

(16) ALIGN(T, Right, Syllable, Right) – align the tone at the right edge of the syllable.

(17) MAXLINKMora[T][11] – Do not lose an association between a mora and a tone.

[10] This is also the approach taken by Duanmu (1994) in arguing for the mora as the TBU, though he assumes constraints that hold only of underlying representations in a derivational theory.

[11] See Morén (1999) for the justifications and use of MAXLINKMora constraints. This constraint will play a larger role in section 5, where it is ranked above the alignment constraint in the post-lexical phonology.

(18) Contrastive high tone in citation CVV

	H | μμ V /na/ 'aunt'	ALIGN-Right	ALIGN-Left	MAXLINKMORA[T]
a.	H | μμ V na	*!		
☞ b.	H | μμ V na		*	*

(19) Contrastive low tone in citation CVV

	L | μμ V /na/ 'custard apple'	ALIGN-Right	ALIGN-Left	MAXLINKMORA[T]
a.	L | μμ V na	*!		
☞ b.	L | μμ V na		*	*

From the phonetic realization of the contour tones, we deduce that both moras are specified for tone: the first tone is on the left mora and the second tone is on the right mora. To ensure that the alignment constraint does not force deletion of the tone that is not aligned at the right edge of the syllable, the faithfulness constraints against deletion must rank above the alignment constraint.

(20) Contrastive falling tone in citation CVV

	/na:-HL/ 'face'	MAX[H]	MAX[L]	ALIGN-Right
a.	L | μμ V na	*!		
b.	H | μμ V na		*!	
☞ c.	HL | | μμ V na			*

The phonetic realizations also suggest that both tones of a contour are not associated with the rightmost mora. Therefore, a constraint against having two tones within the same mora domain (the sharing of a mora by two tones) must be ranked above the alignment constraint. This ranking will be supported independently below.

(21) *[TT]μ: two tones within the same mora domain are prohibited (similar to the constraint in (11), also proposed by Yip (2002:197) as ONE-T/μ).

(22) Contrastive rising tone in citation CVV

<table>
<tr><th></th><th>/na:-LH/ ‘thick’</th><th>*[TT]μ</th><th>ALIGN-Right</th></tr>
<tr><td>a.</td><td>LH
V
μμ
V
na</td><td>*!</td><td></td></tr>
<tr><td>☞ b.</td><td>LH
| |
μμ
V
na</td><td></td><td>*</td></tr>
</table>

We also know by examining the phonetic realizations that the simple tones are not distributed evenly over both moras. This is most obvious in the high tone, where there is a change of direction between the first and second moras, but also true of the low tone, in that the tone is phonetically falling, not level low, and the low pitch target is not reached during the first mora. Therefore, we must rank a constraint against the sharing of tones by two moras above the constraint against aligning the tone to the left edge of the syllable.

(23) *[μμ]T – two moras within the same tonal domain are prohibited (called MONO-SPAN by Bickmore (1996), *MULTIPLE LINK, *SHARE or *SPREAD)

(24) Lack of mora sharing by a citation high tone on CVV

<table>
<tr><th></th><th>/na:-H/ ‘aunt’</th><th>*[μμ]T</th><th>ALIGN-Left</th></tr>
<tr><td>a.</td><td>H
Λ
μμ
V
na</td><td>*!</td><td></td></tr>
<tr><td>☞ b.</td><td>H
|
μμ
V
na</td><td></td><td>*</td></tr>
</table>

Finally, because there is no lexical (phonological) or phonetic contrast between a long level tone and a regular level tone, and to keep the representations as economical as possible, we must assume that this language does not allow two adjacent identical tones within the same syllable (for discussions of tonal OCP see Leben 1973; Goldsmith 1976; Lorentz 1995; de Lacy 1999; Yip 2000; Orcutt 2003; Anttila 2003, etc.). This assumption is also supported by the phonetic realization of the tones in citation forms.

(25) *[HH]σ – two high tones within the same syllable domain are prohibited.

(26) *[LL]σ – two low tones within the same syllable domain are prohibited.

(27) Contrastive high tone in citation CVV

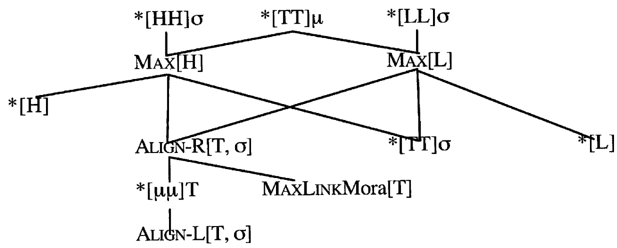
	/na:-HH/ 'aunt'	*[HH]σ	MAX[H]
a.	HH | | μμ V na	*!	
☞ b.	H | μμ V na		*

(28) Contrastive low tone in citation CVV

	/na:-LL/ 'custard apple'	*[LL]σ	MAX[L]
a.	LL | | μμ V na	*!	
☞ b.	L | μμ V na		*

The ranking of tone constraints determined by the tonal contrasts and phonetic realizations in CVV, CVS and CVVS syllables is given in (29).

(29) Summary ranking



With this constraint ranking, mid tone (lack of tone) comes for free, as seen in (30). In the absence of a highly ranked markedness constraint requiring the presence of a tone, the *[H] and *[L] markedness constraints will prefer an output without a tone if the input is unspecified for tone. This is important because it demonstrates that moras/syllables are not (in general) required to bear tone in this language.

(30) Contrastive mid tone in citation CVV

	/na:/ 'rice field'	*[H]	*[L]
a.	H | μμ V na	*!	
b.	L | μμ V na		*!
c.	HL | | μμ V na	*!	*!
d.	LH | | μμ V na	*!	*!
☞ e.	μμ V na		

In order to account for the five lexically contrastive tones of Thai, the analysis proposed here requires the use of four constraints (*[TT]μ, *[μμ]T, ALIGN-R[T, σ], ALIGN-L[T, σ]) that would not be needed under the assumption that tones are associated to syllables. Each of these constraints, however, has been posited in the literature as necessary in the phonology of other languages. Further, the overall phonological system of Thai is in fact simplified. This section has demonstrated that association of tones to moras allows a very straightforward mapping from phonological specification to phonetic realization in sonorant-final syllables: phonetic high and low pitch targets corresponding to phonological H and L are aligned at the right edges of the phonologically specified moras. On moras unspecified for tone, pitch remains in the mid range. (Imagine, in contrast, the complicated phonetic mapping that would be required to create a scooped contour from a simple H associated to the syllable node.) The next section demonstrates how these proposed representations make possible an account of the distributional gaps in obstruent-final syllables, markedness paradoxes that have resisted analysis in previous work. Section 5 will show that our representations lead to a straightforward analysis of the otherwise surprising tonal realizations in connected speech.

4.4. *Tones in CVVO and CVO Syllables*

With an explanation of the distribution of tones in CVV, CVS and CVVS citation forms, we now turn to our markedness paradoxes and the analysis of syllables closed by obstruents. Let us begin with those containing long vowels. These syllables must be realized with either low or falling tone, not mid, high, or rising. The descriptive generalization is clear: these syllables must end low. We link this generalization to the fact that coda obstruents in Thai are both voiceless and glottalized, and propose a constraint that glottal codas must be associated with low tone, given in (31).[12]

(31) C.G.Coda–> L: constricted glottis coda segments must be associated with low tone.

As was discussed in section 1, previous accounts (Gandour 1974a; Zhang 2002) have suggested that rising contours are prohibited on

[12] As we will see in the discussion of CVO syllables, the low pitch associated with glottalized coda consonants must be a phonological tone, not simply the phonetic realization of glottalization, because CVO syllables may end phonetically and phonologically high despite glottalization.

obstruent-final syllables because these syllables are relatively short. Such an approach fails, however, to account for the absence of simple mid tones on these syllables, and for the fact that the high tone, which is in fact phonetically realized as a rise in the second half of the syllable, can appear on CVO, the very shortest syllable type in Thai, but not on CVVO. Yip (1982, 2002) links the absence of rising tones to glottalization, as is proposed here, but her negative constraint "*LH[+glottal]" rules out only rising tones and does not generalize to the other gaps in the tonal system. In contrast, the constraint proposed above, *requiring* the presence of low tone, rules out all three prohibited tones (high, mid, and rising) on CVVO. (We account below for the presence of high, rather than falling, on CVO.)

This constraint is phonetically grounded in the fact that specifications for glottalization and for tone target the same articulator, and may share acoustic cues. The relationship between voiced onsets and low tone, and voiceless onsets and high tone, is well-established in the literature (e.g., Gandour 1974c; Hombert et al. 1979; Yip 2002). The relationship between tone and coda consonants has been less clear, however.

According to Maddieson (1977), "a simple cessation of voicing in [coda] position could readily be reinterpreted as a laryngeal segment." As voicelessness is reinterpreted as phonological laryngealization, the laryngealization may in turn lead to increased vocal fold stiffness and slower vibration prior to complete glottal closure. Pierrehumbert (1995) and Huffman (1998) demonstrate irregular low-frequency glottal pulsing arising from glottalization in English. Abramson (1962) documents glottalization of final consonants in Thai, accompanied by low-frequency glottal pulses on the preceding vowel. These low-frequency pulses may give rise to the perception of low tone. The phonologization of that percept is the constraint in (31). Such a progression is given further support by Diller (1996), who shows that unvoiced segments were associated with non-high tones in the development of Thai.

The cross-linguistic relationship between tone and the laryngeal features of coda consonants is complicated, however (Hyman 1976; Maddieson 1976, 1977). Mithun (1999:24-26) lists a dozen languages or language families of North America for which she argues that glottalized codas or glottal stops gave rise to low tone. On the other hand, Hombert et al. (1979) propose a historical relationship between glottalized codas and high tone in a number of Asian languages. Maddieson (1976, 1977) cites three cases (Navajo, Kiowa, and Kapanahua) where glottalized codas are associated with low tone and four cases (Jeh, Vietnamese, Danish, and Latvian) where glottalized codas are associated with high tone. Maddieson specifically argues that the association between high tone and glottalization comes about when, in order to reach a high pitch at the end of a long syllable, the vocalis muscle is tensed beyond the parameters necessary to continue modal voicing. Mithun suggests, however, that while high tones may give rise to vocal fold tension that induces glottalization, the glottal constriction, once present, will cause low-frequency pulses that can create the perception of *low* tone. This progression – high tone leads to glottalization, but glottalization, leads to low tones – may account for the cross-linguistic variation. Yip (2002:204) suggests that such a progression may have taken place diachronically in Thai.

There may be additional articulatory, as well as acoustic, factors supporting an association between glottal codas and low tone. Extra glottal tension may be recruited to reach low tones as well as high: a speaker's voice can "crack" at both extremes of her or his range. Pierrehumbert (1990:388) notes that the "the mechanism for active F0 lowering, such as is found for L pitch accents... is complex and poorly understood" and suggests that a number of different muscles may be involved. Erickson (1976, 1994) and Erickson and Abramson (1972) found active tensing of the vocalis muscle itself in only one context – the end of the falling tone. Thus, the phonetic evidence suggests that low tone and glottalized codas will tend to reinforce one another both articulatorily and perceptually. In Thai, the presence of a glottalized coda can give rise to the perception that a syllable ends in a low tone, and a syllable that ends with a very low pitch target may induce extra tension of the vocalis that may reinforce the presence of a glottalized coda.

We now turn to working out the phonological consequences of the constraint requiring that coda obstruents have low tone. High ranking of C.G.Coda–>L in the constraint hierarchy directly solves our first markedness paradox. Regardless of the input tonal sequence, only low and falling tones will surface on CVVO syllables.

Tableau (32) shows that if there is no underlying tonal specification, a CVVO syllable will surface low-toned if C.G.Coda–>L is ranked above the constraint against low tone.[13] Since our constraint is of a positive nature, *requiring* the presence of a low tone, mid tones,

[13] This constraint must also be ranked above a faithfulness constraint against adding tones that were not in the input (e.g. DEP[L]). We do not discuss DEP[T] constraints because they are not highly ranked in Thai and as such are not functionally distinguishable from the negative markedness constraints of the *[T] family.

with no tonal specification at all, cannot surface on these syllables. Crucially, we assume that the second mora is shared by both the vowel and the obstruent coda consonant, an assumption supported by the duration measurements reported above.

(32) Markedness paradox 1: Neutralisation to low in /CVVO/

	/la:k/ 'various'	C.G.Coda-->L	*[L]
☞ a.	L | μμ \/\\ l a k^ʔ		*
b.	μμ \/\\ l a k^ʔ	*!	

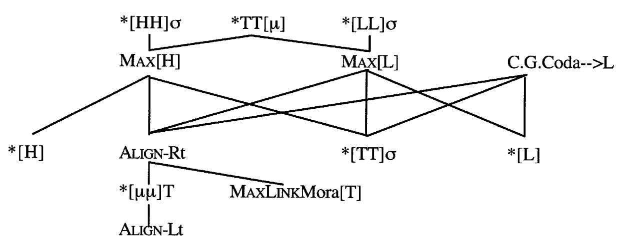
A falling tone will surface if there is a high tone in the input, accounting for the second markedness paradox – the lack of surface high tone on these syllables. If there is a high tone in the input of a CVVO syllable, ranking of C.G.Coda– > L above both *[TT] σ and Align-Right ensures that a falling tone surfaces.

(33) Markedness paradox 2: Neutralization to falling tone in /CVVO-H/

	/la:k-H/ 'to tow'	C.G.Coda-->L	*[TT]σ	Align-Right
☞ a.	HL | | μμ \/\\ l a k^ʔ		*	*
b.	H | μμ \/\\ l a k^ʔ	*!		

Adding the C.G.Coda– > L constraint to the ranking already established, we find the following hierarchy.

(34) Summary ranking



With this ranking, input CVVO syllables with either a low tone or no tone will surface as low, and an input with a high tone or falling tone will surface as falling.[14]

The final question to ask is what the output would be if the input has a rising tone sequence.[15] We assume that both C.G.Coda– > L and MAX[H] outrank LINEARITY, so that a surface falling tone results.[16]

(35) LINEARITY – Preserve the linear order of features and segments (McCarthy and Prince 1995).

(36) Rising tone neutralization to falling in /CVVO/

	/la:k-LH/ 'to tow'	MAX[H]	C.G.Coda-->L	LINEARITY
a.	L | μμ \/\ l a k^2	*!		
b.	LH | | μμ \/\ l a k^2		*!	
☞ c.	HL | | μμ \/\ l a k^2			*

[14] Note that this analysis would be much more complicated and less explanatory if the TBU were the syllable. If C.G.Coda– > L required only that a syllable containing an obstruent coda have a low tone associated to it, a rising tone (LH) would be equally acceptable. A possible repair to the syllable-based analysis would be the addition of a constraint requiring that low tones resulting uniquely from glottalized codas be aligned to the right of the syllable. This alternative analysis, suggested by an anonymous reviewer, is purely descriptive and fails to provide a simple, non-stipulative explanation. Our analysis using moraic association straightforwardly allows the L tone to be uniquely associated to the second half of the syllable. Another reviewer points out that a representation in which the low tone had an L linked to both moras would also be consistent with the requirements of C.G.Coda– > L. This is true, but a doubly linked L (and the doubly linked H for the high tone that would be required by a consistent constraint ranking) would less accurately reflect the phonetic F0 contours.

[15] This input must be assumed because of Richness of the Base (Prince and Smolensky 1993).

[16] Ranking C.G.Coda– > L and Linearity above MAX[H] would result in an output with a low tone. However, this ranking is contradicted by the data analyzed below.

Thus, no matter what the tonal specification of the input is, C.G.Coda–>L (in conjunction with the rankings already established) ensures that a CVO output must have either a low or falling tonal pattern.

Finally, we turn to the CVO syllables, where the only tones allowed are simple H and L. These syllables have the inherent difficulty that voiceless obstruents cannot realize tone. Without vibration of the vocal folds, no tone can be produced or heard. Therefore, any tonal contrast must be realized on the mono-moraic vowel. We will formalize this with the constraint "REALIZETONE" given in (37), and we propose that this constraint falls within the same family of constraints as REALIZEMORPHEME (Kurisu 2001). (See also Yip (2002) *[-son]Tone.) Since we wish to avoid making claims about the specification of individual segments for the phonological feature [voice], we suggest that this constraint be thought of as having a perceptual, rather than an articulatory, grounding.

(37) REALIZETONE: Tones must be associated to a segment that can support vocal fold vibration.

In CVVO syllables, the association of the tone with the final obstruent presented no problem with respect to REALIZETONE. C.G.Coda–>L requires that a low tone be associated to the mora that is linked to the final consonant, but since that second mora is shared between vowel and consonant, the tone can be realized on the vocalic portion of the mora and a low or falling specification results. However, although CVO syllables have two moras, only one is able to realize a tone.

We propose that a low tone or no tone in the input results in an output with a low tone linked to both moras, thus satisfying both C.G.Coda–>L and REALIZETONE. This is shown in tableaux (38) and (39). Note that the inputs in these two tableaux have the same meaning but different underlying tonal specifications to satisfy Richness of the Base.

(38) Contrastive low tone in /CVO-L/ with tone shared by moras

	/lak-L/ 'steak'	REALIZETONE	C.G.Coda-->L	*[μμ]T
a.	μμ | | l a k^ʔ		*!	
b.	L | μμ | | l a k^ʔ	*!		
☞ c.	L Λ μμ | | l a k^ʔ			*

(39) Tone neutralization to low tone in /CVO/ with tone shared by moras

	/lak/ 'steak'	REALIZETONE	C.G.Coda-->L	*[μμ]T
a.	μμ | | l a k^ʔ		*!	
b.	L | μμ | | l a k^ʔ	*!		
☞ c.	L Λ μμ | | l a k^ʔ			*

Yet, high tones can also occur on CVO syllables. If there is a high tone in the input, it must surface. Tableau (39) shows that we can account for this if both REALIZETONE and MAX[H] outrank C.G.Coda–> L. Associating a low tone to the coda is important, but realizing an underlying high tone is even more so.

(40) Contrastive high tone in /CVO-H/ syllables

	/lak-H/ 'to steal'	MAXH	REALIZETONE	C.G.Coda-->L
a.	μμ | | l a kˀ	*!		*
b.	L | μμ | | l a kˀ	*!		
c.	HL | | μμ | | l a kˀ		*!	
☞ d.	H /\\ μμ | | l a kˀ			*

In CVO syllables, the tone is necessarily shared by both moras, even when it is a high tone. This is due to a combined ranking of REALIZETONE and ALIGN-Right above *[μμ]T. It is important to note that this coerced tone-sharing accounts for the phonetic realization of the high tone. That is, if the high tone aligned only to the coda obstruent, it would not be realized, and if it aligned only to the vowel, it would be realized as a rapid rise, not a scooped contour.

(41) Contrastive high tone in /CVO-H/ syllables

	/lak-H/ 'to steal'	REALIZETONE	ALIGN-Right	*[μμ]T
a.	H | μμ | | l a kˀ	*!		
b.	H | μμ | | l a kˀ		*!	
☞ c.	H /\\ μμ | | l a kˀ			*

Contour tones can be ruled out in CVO syllables by ranking the prohibition against two tones associating to a single mora (i.e. *[TT]μ) above C.G.Coda–> L.

(42) Neutralization of falling tone to high tone in CVO syllables

	/lak-HL/ 'to steal'	REALIZE TONE	*[TT]μ	C.G.Coda-->L
a.	HL \/\ μμ | | l a $k^{ʔ}$		*!	
b.	HL | | μμ | | l a $k^{ʔ}$	*!		
☞ c.	H /\ μμ | | l a $k^{ʔ}$			*

(43) Neutralization of rising tone to high tone in CVO syllables

	/lak-LH/ 'to steal'	REALIZE TONE	*[TT]μ	C.G.Coda-->L
a.	LH /\/ μμ | | l a $k^{ʔ}$		*!	
b.	LH | | μμ | | l a $k^{ʔ}$	*!		
☞ c.	H /\ μμ | | l a $k^{ʔ}$			*

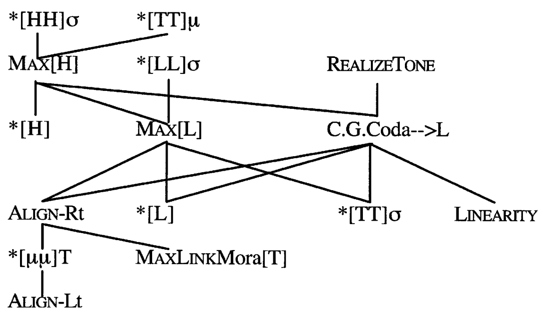
Finally, since high tones arise despite the pressure to have low tones associated with coda obstruents, MAX[H] must outrank MAX[L].

(44) Neutralization of falling tone to high tone in CVO syllables

	/lak-HL/ 'to steal'	MAX[H]	MAX[L]
a.	L /\ μμ | | l a $k^{ʔ}$	*!	
☞ b.	H /\ μμ | | l a $k^{ʔ}$		*

Our proposed ranking of all the constraints on tonal association is given in (45). This constraint ranking accounts for the distribution of tones in all citation forms, and straightforwardly solves the two markedness paradoxes. Note that the phonological and phonetic facts complement one another and are modeled using well-motivated, simple constraints that are, for the most part, already established in the literature.

(45) Constraint ranking for Thai tones in citation forms



5. Tone Realizations in Connected Speech

5.1. *Phonetic Data*

With the description and analysis of tones in citation forms established, we move to connected speech. Very interesting differences from citation form are seen when the tones are found in non-final positions. Figure 6 shows exemplar tonal contours (again the second repetition of three in each case) of the CVS, CVVS, CVO and CVVO syllables in the m_m sentence context. As in Figure 4, the lexical rising and falling tones are graphed with dashed lines. The lexical "falling" tones are the ones at the top of the range and the lexical "rising" tones are the ones at the bottom.

As we can see in these figures, there is little variability in tonal shape due to syllable type. (Mean pitch targets and pitch changes over each mora in connected speech are given in Table II). For both speakers, the high, mid and low tones have much the same shapes in connected speech as in citation form:

- Low tones fall smoothly over the course of the syllable and end at the bottom of the range, near 175 Hz;
- Mid tones stay flat, remaining in the middle of the range; and

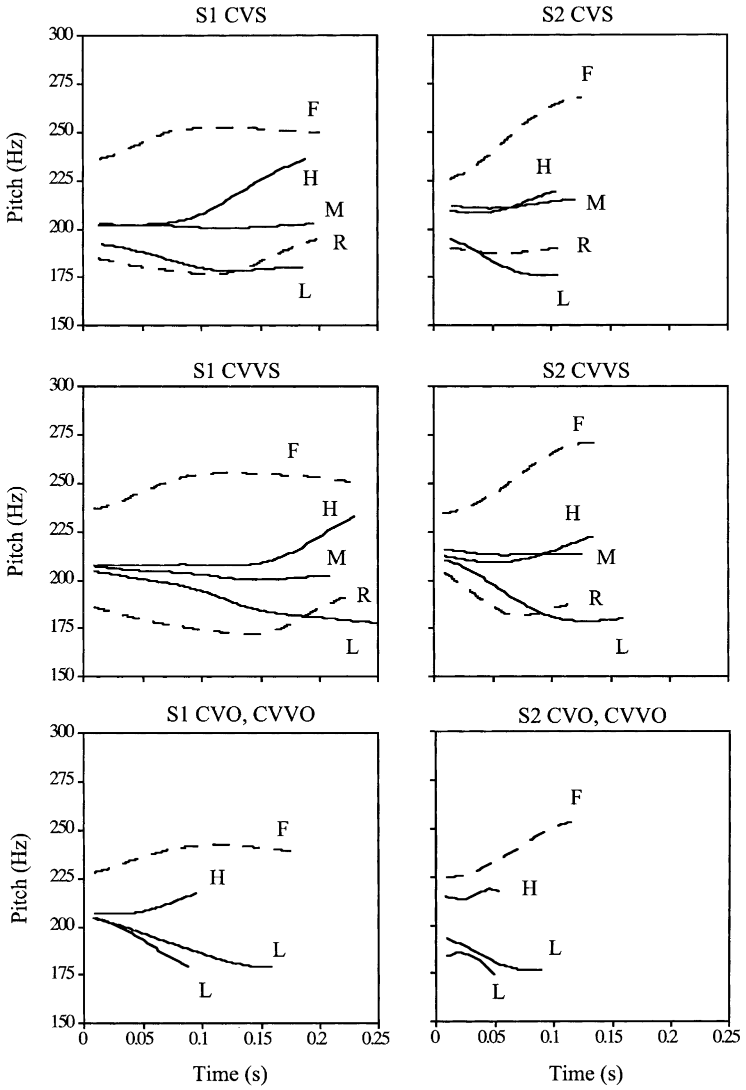


Figure 6. Exemplar pitch contours for the five contrastive tones in the m_m sentence context. Speaker 1, left, Speaker 2, right.

- High tones begin in the mid range, remain fairly flat during the first mora, and then turn upward during the second. In CVO syllables, the sonorant portion is very short (and thus so is the pitch contour), but the shape is the same as in the longer syllables.

A comparison with Figure 4 also reveals that overall pitch range is not much compressed in connected speech as compared to citation

TABLE II

Pitch targets (in HZ) at salient points in the connected speech tonal contours, and mean pitch change over each mora, averaging over all CVV, CVS, and CVVS syllables ($n = 9$) for each speaker

		Pitch at vowel onset	Pitch at end of μ1	Pitch at end of μ2	Pitch change over μ1	Pitch change over μ2
S1						
Falling	m_m	234	255	251	21	−4
	h_h	255	265	244	10	−21
	l_l	217	251	220	34	−31
Rising	m_m	198	173	201	−25	29
	h_h	211	177	198	−34	21
	l_l	188	172	212	−15	40
High	m_m	212	204	236	−8	31
	h_h	227	212	231	−15	19
	1_1	198	193	231	−5	38
Mid	m_m	214	204	205	−10	1
	h_h	237	214	211	−23	−3
	l_l	204	198	195	−7	−3
Low	m_m	211	187	178	−24	−9
	h_h	228	190	182	−38	−8
	l_l	189	175	162	−13	−13
S2						
Falling	m_m	233	261	275	28	14
	h_h	241	256	257	16	1
	l_l	201	238	229	37	−9
Rising	m_m	205	178	189	−28	11
	h_h	231	187	178	−44	−9
	l_l	177	166	181	−11	15
High	m_m	223	205	220	−18	15
	h_h	238	223	229	−15	6
	l_l	189	186	207	−3	21
Mid	m_m	221	209	209	−13	1
	h_h	248	232	221	−16	−12
	l_l	192	189	186	−3	−3
Low	m_m	213	182	179	−31	−3
	h_h	244	203	183	−42	−20
	l_l	184	174	169	−10	−5

form. However, non-final connected speech tokens depart from the canonical citation shape in two important ways:

- Falling tones do not fall for either speaker. In fact, particularly for Speaker 2, the "falling" tone actually rises for most or all of its duration.

- Our two speakers differed regarding rising tones. Speaker 1 showed a consistent rise (albeit not to the extreme seen in citation form), but Speaker 2 showed little if any rise.

The lack of falling offsets for falling tones, and variability in rising offsets for rising tones, are consistent with the shapes of these tones in connected speech reported in earlier studies. As discussed in section 1 above, Abramson (1979), Gandour et al. (1994), and Potisuk et al. (1997) all reported contour tones that ended no higher than the mid range in connected speech. The data here are most similar to those reported by Potisuk et al., the only other previously published study to include young, urban females.

Figure 7 shows exemplar tonal contours in the h_h and l_l contexts. There is clear evidence of phonetic perseverative tonal coarticulation: all tones begin higher in the h_h context and lower in the

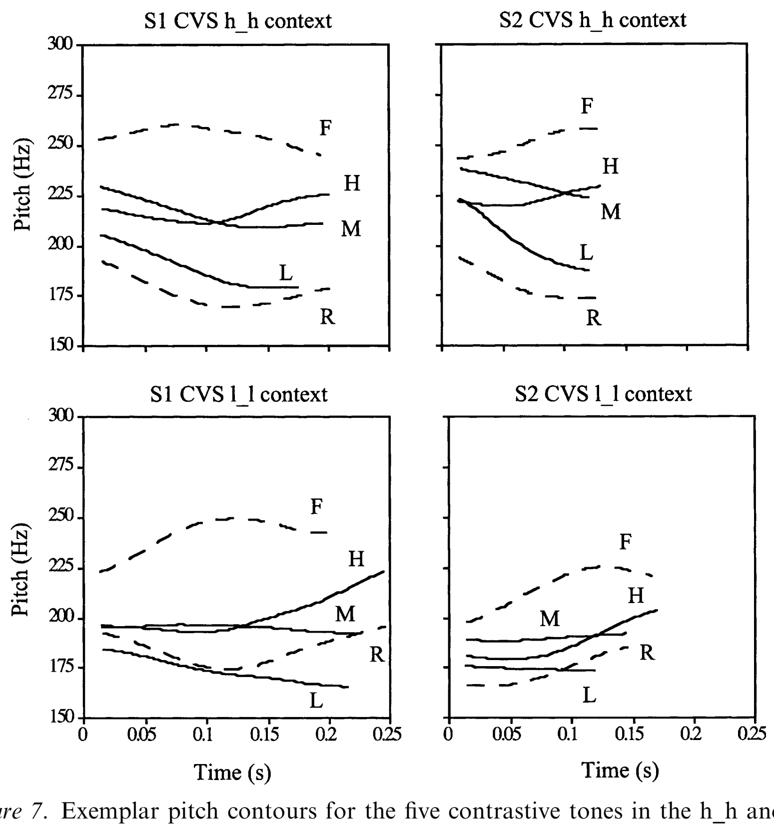


Figure 7. Exemplar pitch contours for the five contrastive tones in the h_h and l_l sentence contexts. Speaker 1 (left), Speaker 2 (right).

l_l context. This is again consistent with Abramson (1979), Gandour et al. (1994), and Potisuk et al. (1997), as well as with our claim that tonal targets are aligned at the right edges of moras. The fact that phonetic coarticulation is perseverative, rather than anticipatory, is seen particularly clearly in the realizations of the low tone for Speaker 2. Surrounded by two other low tones (bottom right), the low for this speaker remains fairly level at the bottom of the range. When surrounded by two high tones (top right), the low tone is realized as a steep and smooth fall, with a high point reached just at the release of the onset consonant, and the low point reached at the end of the syllable. Clearly, it is the preceding high tone, not the following one, that has the greatest influence. (The tonal contours are also realized within a slightly lower overall range in the l_l context than in the h_h context. It is not clear, however, whether this is an effect of coarticulation or declination, since the target tones in the l_l context occurred later in a longer sentence.)

It is important to note, however, that the perseverative coarticulation is not phonological: there is no phonological spread of tone from one syllable to the next. If the H of a preceding high tone were to phonologically re-associate with the first mora of a following low-toned syllable, for example, we would expect the high pitch peak to be reached in the middle of the target syllable (the right edge of the first mora), not at its extreme left edge. Although the pitch falls over the course of a low-toned syllable in the h_h context, the distinction between a lexical low tone and a lexical falling tone is not neutralized. Rather, as noted above, the pitch realizations in the h_h and l_l contexts are exactly as predicted if there is no phonological tone spread, but if tonal targets are aligned as far right in the syllable as possible.

Other than beginning somewhat higher or lower, the tonal shapes in the h_h and l_l contexts are consistent with those in the m_m context. For both speakers, the falling tones fall only slightly if at all; in all contexts the lexical falling tone ends at a higher pitch than the lexical high tone. The two speakers differed in the realization of the rising tone. Rising tones for Speaker 1 showed a consistent (though not dramatically large) fall-rise contour, falling an average of 25 Hz over the first mora of the syllable and then rising an average of 30 Hz over the second mora to end in the mid range, as shown in Table II. For Speaker 2, rising tones also consistently fell over the first mora (an average of 28 Hz), but for this speaker pitch either continued to fall or rose only slightly (15 Hz or less) during the second mora. For

Speaker 2, "rising" tones never rise out of the low region of the pitch range.

Note, however, that even with the loss of an actual fall or rise for the contour tones, all five tonal shapes remain distinct in all contexts. Again consistent with previous findings, there is no phonological sandhi or neutralization. Although the high and mid tones are close in some contexts (particularly for Speaker 2), they can be distinguished in that the high tone is trending upward at the end of the syllable, while the mid tone is level or trending downward.

What has happened to the "missing" high and low offsets of the contour tones? There are three possibilities. The realization of the H and L pitch targets might be delayed until a later syllable, due to either a phonological reassociation or a delay in phonetic timing. The second halves of the contours might be phonologically and phonetically present on the target syllables, but subject to reduction. Or the second H and L autosegments may be phonologically deleted. We will argue that the last option is the correct one.

It is not the case that the missing high and low pitch targets are just realized on a later syllable. Studies of other languages, such as Xu (1999b) for contour tones in Mandarin and Arvaniti et al. (1998) for complex pitch accents in Greek, have found that in connected speech the actual maximum pitch excursion in complex contours (the final high of the rising tone and the final low of the falling tone) may in fact be realized at the beginning of the following syllable. This "peak delay", it is hypothesized, comes about because a single syllable does not afford enough time to articulate densely specified tonal targets. A related process, rightward "tone shift", in which a tone that originates on one syllable is phonologically re-associated one syllable to the right, has been described in many African languages (e.g., Hyman and Schuh 1974; Clements and Ford 1979; Odden 1995, and references therein).

There is, however, no evidence of peak delay or tone shift in Thai. If the final L and H of the falling and rising tones had been delayed in the Potisuk et al. and Gandour et al. data, there would have been a finding of greater perseverative coarticulation following these syllables, rather than the actual finding of no significant effect at all. Potisuk et al. (1997) explicitly consider the peak delay hypothesis for Thai. (Peak delay could not be tested in Abramson (1979) or Gandour et al. (1994) because intervening onset obstruents created gaps and perturbations in the F0 contour at the crucial junctures.) Potisuk et al. found that when tones with a high offset (high and rising) were followed by tones with an initial fall (low or rising), the final high peak was actually realized slightly earlier in the target syllable, not later, the opposite of tone delay. The authors attribute this effect to a need "to allow for a less abrupt change in [the] acceleration that is required in making transition to a following tone with a low onset" (p. 34). There was no evidence of either peak delay or peak advancement in low, mid, or falling tones. The authors do note that when a syllable that ends high is followed by a syllable that begins high, then the peak "may or may not be realized with the boundaries of a single syllable in running speech" (p. 34). As Xu (1999b) points out, however, the exact alignment of an F0 peak can only be tested in those cases where the pitch trajectory is expected to change direction from one syllable to another.

In the present experiment, it is true that there is generally a drop in pitch back to the mid range on a syllable following a falling tone. Since falling tones are realized at the top of the range, there is generally nowhere for the pitch on the next syllable to go but down, and we interpret this drop in pitch as a return to the default setting on a phonologically toneless mora. As noted by Pierrehumbert (1980:37), describing the pitch trajectory following H* accents in English, "the F0 falls until it is time to start aiming for the next H* level." Again, this is consistent with the finding of Erickson (1976, 1994) that relaxation of the cricothyroid muscle after the attainment of a high pitch target, without any other muscle activation, results in a fall back to the mid range. Such resetting can also be seen following lexical high tones, as in the realization of the mid tone in the h_h context (Figure 7). If there were reassociation or delay of the L of a falling contour in Thai, a fall to the bottom of the pitch range on the next syllable, not a gradual drop, would be expected.

The only time a lexical falling tone is not followed by a phonetic fall on the next syllable is when that next syllable is itself a lexical falling tone (the only tone type, we argue, where the first mora is specified as high). Sequences of falling tones were not systematically analyzed in our data, but were elicited by Kallayanamit (2004), in an unpublished study of the intonation patterns of five young female speakers of the Bangkok dialect.[17] In Kallayanamit's recordings of sentences that consist only of morphemes with lexical falling tones, the most common pattern was for the fall to be suspended on all

[17] Neither of the speakers in the present study participated in Kallayanamit's study.

syllables but the one in phrase-final position. An example pitch track from Kallayanamit (2004:204) is shown in Figure 8. Each of the six syllables in the phrase, /pʰî: nâ:t, nân klâj klâj nîm /, 'Brother Nart, sit near Nim,' carries a lexical falling tone. Yet there is a phonetic fall on only two syllables. The pitch on the syllable /pʰî:/ is partially obscured by aspiration, but it clearly ends in the high range, around 275 Hz. The next syllable, /nâ:t/, which is both prominent in the utterance and pre-pausal, carries the full rise-fall contour. The second half of the utterance begins with a slight rise on /nân/ then continues as a high plateau, at around 290 Hz, over the non-final syllables, falling (to the bottom of the pitch range) only on the last mora of the utterance.

We conclude that the H and L pitch offsets of the contour tones in Thai are not realized on adjacent syllables in connected speech, but are in fact curtailed. The remaining question is whether this change in contour shape is a matter of phonetic reduction or phonological deletion. The answer depends on how one interprets slight drops in pitch. Are they evidence of a (reduced) phonological L specification, or not?

We argue, based on Erickson's (1976, 1994) EMG data, and on the acoustic data that shows pitch falling back to the mid range when there is no phonological evidence for any low target (as on the

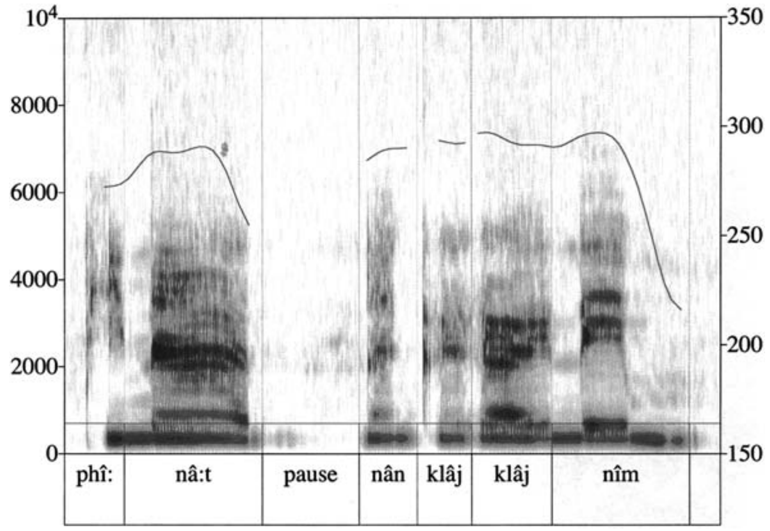


Figure 8. Spectrogram and pitch track of a sequence of six falling tones, from Kallayanamit (2004).

first mora of a high tone, or mid tones in a high tone context) that there is a phonological L specification in Thai only when pitch is lowered to the bottom third of the speaker's range. Pitch falls of lesser extent are assumed to be the result of the return to a default state upon relaxation of the pitch-raising cricothyroid. Exactly how far and fast the pitch falls will depend on other phonetic factors, such as speaking rate and tonal context, and probably also on sociolinguistic factors, such as gender and age. Thus falling tones in connected speech may fall to the mid range for older males speaking shorter utterances more slowly (as perhaps in Abramson's 1979 study) or not at all for younger females speaking longer utterances more quickly (as for our Speaker 2, or the speakers in Kallayanamit's 2004 study), or somewhere in between (as for our Speaker 1, or in Potisuk et al. 1997). Regarding the effect of speaking rate, Gandour et al. (1999) found that falling, high, and rising tones in unstressed syllables had "flatter" excursions at a fast speaking rate than at a slow one, though that study unfortunately did not separate stress and utterance position, which may explain why high tones were also affected. There is thus variability reported in whether falling tones fall somewhat or not at all, but in all the data in all the sources discussed, Thai falling tones in connected speech never fall below the mid range, and we thus argue that the low pitch target of the falling tone is phonologically deleted in connected speech.

Given that falling pitch is the default when there is no target, and given that Erickson (1976, 1994) found cricothyroid activity for all pitch raising, whether from low to mid or from mid to high, we interpret any significant rise in pitch as the presence of an H target. Thus we argue (consistent with the coarticulatory findings of Potisuk et al. 1997) that there is variability in deletion of the H target on rising tones in connected speech. We will argue that our Speaker 1 does not delete the H of rising tones, but our Speaker 2 does.

An alternative position would be to assume that falls to the mid range (as in the Abramson 1979 data) are evidence of a (reduced) phonological L specification, and that only a truly flat trajectory is evidence of phonological deletion. We do not believe that this position is consistent with the rest of the phonetic and phonological data on Thai, but it is not *prima facie* unreasonable. This is the position taken by Ladd and Schepmann (2003), for instance, in claiming that English pitch accents usually transcribed as H* are in fact L+H*. They argue that the slight pitch fall that precedes the H should be seen as evidence of a L target, not as a return to default pitch level, as had been assumed by Pierrehumbert (1980) and other researchers following her lead. There are, however, numerous cases in our data (Figures 7 and 8), and in the data of Potisuk et al. (1997) and Kallayanamit (2004, our Figure 8), where falling tones do not fall at all. If one assumes phonological deletion only for these cases, then one might say that young, urban females (who are represented in these studies only) had phonologized a process that is only a phonetic tendency for older speakers. It would be a great stretch, however, to argue for phonetic reduction rather than phonological deletion in these cases. (It has been demonstrated previously that phonetic or phonological delay is not a viable analysis.) If only phonetics is involved, one would have to assume a reduction that selectively targets only the offsets of the contour tones, not other high and low points in the pitch trajectories, and that reduces just those points to such an extent that falling tones end at the top of the pitch range rather than at the bottom. One would have to argue for a phonetic implementation in which the phonological L of the rising tone causes a pitch drop to the bottom of the range, while the phonological L of the falling tone has no phonetic realization at all.

We conclude that, at least for the data presented here, the lexically specified L of the falling tone for both speakers, and the lexically specified H of the rising tone for Speaker 2, are phonologically deleted in connected speech.

We turn now to the problem of how and when this phonological deletion can be accomplished. How can the phonetic shapes seen in Figures 6 to 8 be reconciled with the phonological descriptions? How can lexically falling tones be realized as acoustically rising, and lexically rising tones as acoustically falling in a language in which there is no tone sandhi? What is the relationship between citation forms, phrase-final connected speech, and non-phrase-final connected speech such that citation and final tokens maintain fully realized contours, but non-final tokens show simplification without contrast neutralization?

Crucially, certain points of the contours are stable across the variant realizations and seem to correspond to the lexical tones. The "high" and "low" tones are high and low only at the end of the syllables. These patterns can be accounted for in a straightforward fashion if the crucial phonological specification (and presumably the crucial perceptual cue) for these tones is an H or L on the second mora, as seen in (46).[18] These are the same representations that were proposed above to account for the phonological distributions of lexical tones and their phonetic realizations in citation form.

(46)

	Structure		Cue
		H |	
High tone	μ	μ	[H]σ
		L |	
Low tone	μ	μ	[L]σ
Mid tone	μ	μ	[ ]σ

In contrast to the downward drift of the "level" tones in the first part of the syllable, the "falling" tone, whether in citation form or running speech, moves to a very high point early in the syllable, a high from which it may or may not phonetically fall. (Recall the finding of Gandour et al. (1991), discussed in section 1, that the high and rising tones could be reliably distinguished based on the timing of the pitch peak – early for falling, later for high – while the rise to, and fall from, the peak could vary in shape and extent.) The "rising" tone falls quickly to the very bottom of the range, where it remains for most of the syllable, then rises only at the end (if at all). Based on these patterns, we assume that the "falling" tone has an H crucially associated to the first mora, and the "rising" tone has an L in that position, as shown in (47). Again, this corresponds exactly to the representation proposed above. The data in Figures 6 to 8 indicate, however, that the tone associated to the second mora of the contour tones can be deleted in non-phrase-final position in some styles of speech.

(47)

	Structure		Cue
	H |	(L) |	
Falling tone	μ	μ	[H]σ
	L |	(H) |	
Rising tone	μ	μ	[L]σ

[18] Controlled perceptual studies testing these hypotheses are currently being undertaken.

Note that because tones are associated to moras, not syllables, the second tone of the contour can be deleted, and the result (HØ or LØ) remains distinct from the simple tones (ØH and ØL). If the syllable were assumed to be the TBU, there would be no way to delete one of the tones in a contour without neutralizing the distinction.

What is the reason, then, for the disparity between citation and some of the connected speech tones? Where does tone deletion take place? We suggest that deletion takes place in an interaction between lexical and post-lexical phonology.

5.2. *Lexical vs. Post-lexical Phonology*

Recall that citation and phrase-final forms have identical, fully realized pitch contours. The thing that these two environments have in common is that they are both found in prominent phrase-final position. This is in contrast with non-phrase-final forms which display limited, non-neutralizing simplification. In order to account for these patterns we will assume (following Kiparsky 1986, 2000) that the Thai grammar consists of two strata, lexical and post-lexical, each with its own slightly different constraint ranking. The output of the lexical stratum becomes the input to the post-lexical stratum.

The lexical phonology establishes contrastive representations (minimally). Simplifying things slightly (e.g. abstracting away from the complicated obstruent-final syllables), the Thai lexical phonology ensures that seven potential input tone combinations correspond to only five possible outputs. This was argued for in section 4.3 above, and is illustrated in (48).

(48)	UR		Lexical output
a. Mid:	/ØØ/	–>	[ØØ]
b. High:	/ØH/	–>	[ØH]
	/HØ/	–>	[ØH] *[HØ]
c. Low:	/ØL/	–>	[ØL]
	/LØ/	–>	[ØL] *[LØ]
d. Falling:	/HL/	–>	[HL]
e. Rising:	/LH/	–>	[LH]

It is the neutralization seen in the high and low tones that is of interest to us here. The lexical constraint ranking in (45) provides the correct input/output pairs for citation forms: the tone alignment constraints force all single tones to be aligned to the rightmost mora of the syllable; however, higher-ranked tone faithfulness constraints allow a second tone to be associated to the leftmost mora as necessary. This means that there are only five lexically contrastive tonal combinations.

What is interesting about the post-lexical phonology is that the following patterns are found:

(49)

	Lexical output		Post-lexical phrase-final output	Post-lexical non-final output	
a. Mid:	[ØØ]	–>	[ØØ]	[ØØ]	
b. High:	[ØH]	–>	[ØH]	[ØH]	
c. Low:	[ØL]	–>	[ØL]	[ØL]	
d. Falling:	[HL]	–>	**[HL]**	**[HØ]**	
e. Rising:	[LH]	–>	**[LH]**	**[LH]**-S1	**[LØ]**-S2

A five-way contrast is maintained in both the lexical and post-lexical phonology, but in the contrast is realized in different ways. Further, while both speakers have the same lexical grammar, they differ slightly in the exact nature of their post-lexical grammars. While both speakers show complete faithfulness to lexical tonal specifications in post-lexical prominent position, Speaker 2 simplifies both contour tones in non-prominent position and Speaker 1 simplifies only the falling tone.

To explain this pattern, we propose that the Thai post-lexical grammar differentiates among four types of positions: phrase-final syllables, non-final syllables, peak moras, and non-peak moras. The resistance of peak moras to losing tones is not surprising since syllable peaks are traditionally considered prominent, and the resistance of phrase-final syllables to losing tones should not be particularly surprising because Thai is an Iambic language (Bennett 1994), thus the head syllables of prosodic feet are on the right edge of phrases.

The post-lexical grammar not only ensures that inputs surface faithfully in prominent syllable position, but also that the first tone of a contour neither deletes in favor of the second tone nor re-aligns when the second tone deletes (see (47)). What is crucial to understanding the tone alternations in connected speech is that the input to the post-lexical component is the output of the lexical component, crucially not the underlying representations. The contrastive lexical tonal system requires that all tones be aligned as far right in the syllable as possible. However, the post-lexical contour simplification involves faithfulness to the leftmost tone and deletion of the rightmost tone, without tonal re-alignment to the right. If the inputs to both the lexical and post-lexical forms were the same, that is if the lexical and post-lexical components were not in a serial relationship, then we could not explain the simplification without neutralization found in connected speech.

In the following sections, we propose an analysis in which the relative ranking of faithfulness constraints and key markedness constraints differs from lexical to post-lexical level. We make use of both Stratal OT (Kiparsky 2000) to differentiate between lexical and post-lexical phenomena, and Positional Faithfulness[19] (Beckman 1995) to differentiate among tonal behaviors in different phonological environments at the post-lexical level.

5.3. *Post-lexical Grammar of Speaker 2*

Since Speaker 2 treats both rising and falling tones in the same manner, while Speaker 1 treats them differently, we begin with analysis of the post-lexical phonology of Speaker 2.

Because the output of the lexical phonology serves as the input to the post-lexical phonology, post-lexical faithfulness constraints require faithfulness to the lexical outputs, not to underlying representations. Thus Richness of the Base does not apply, and forms that are not legitimate outputs of the lexical phonology (such as CVVC syllables with LH tonal specifications) do not have to be ruled out all over again. Because inputs are limited, many of the constraints that were active in ruling out illicit forms in the lexical phonology (such as C.G.Coda– > L) are not active in the post-lexical phonology. (Note, however, that the low ranking of C.G.Coda– > L in the post-lexical component is crucial to our analysis. In the lexical component, final L tones are required on CVVO syllables. In the post-lexical component, these L tones may be lost, resulting in lexical falling tones with no phonetic fall, as in Figure 6.) The crucial constraint interactions in the post-lexical phonology are those between three general markedness constraints (*[H], *[L] and *[TT]σ) and positional faithfulness constraints requiring faithfulness to lexical tones and their moraic associations.

In examining the connected speech of Speaker 2, we find that there is complete faithfulness in phrase-final position. We propose that this must be, as it is in the lexical component, due to relatively high faithfulness, as shown in (51) and (52).

[19] We do not pursue alternative positional markedness possibilities in this paper.

(50) MAXHeadσ[T] – Do not delete a tone from the head syllable of the phrase.[20]

(51) Contrastive high tone in post-lexical phrase-final syllables

	H | μμ V n a ‘aunt’	MAXHeadσ[H]	*[H]
a.	μμ V n a	*!	
☞ b.	H | μμ V n a		*

(52) Contrastive low tone in post-lexical phrase-final syllables

	L | μμ V n a ‘custard apple’	MAXHeadσ[L]	*[L]
a.	μμ V n a	*!	
☞ b.	L | μμ V n a		*

Falling and rising tones are also possible, therefore the faithfulness constraints on each simple tone must outrank a markedness constraint against having two tones per syllable.

[20] This could just as easily be faithfulness to phrase-final position, since there are many claims in the literature that phrase-final is a prominent position regardless of metrical structure.

(53) Contrastive falling tones in post-lexical phrase-final syllables

	H L | | μμ V n a 'face'	MAXHeadσ[H]	MAXHeadσ[L]	*[TT]σ
a.	μμ V n a	*!	*!	
b.	H | μμ V n a		*!	
c.	L | μμ V n a	*!		
☞ d.	H L | | μμ V n a			*

(54)

In non-final position, simple tones also occur. Therefore, general faithfulness constraints must be ranked above their corresponding markedness constraints in the post-lexical component. Note that this is the same for both the lexical and post-lexical grammars.

(55) MAX[T] – Do not delete a tone.

(56) a. MAX[H] >> *[H]
b. MAX[L] >> *[L]

Where the lexical and post-lexical grammars differ is in the realization of the contour tones. In non-final position in connected speech (for this speaker), both contour tones lose one of the tones of the sequence. Thus, in contrast to the lexical ranking, the constraint against two tones in a syllable must be ranked above the general faithfulness constraints in the post-lexical component.

(57) *[TT]σ >> MAX[H], MAX[L] (post-lexical)

However, it is always the second tone that is lost. Therefore, faithfulness to the head (initial) mora of the syllable must be ranked above general faithfulness, as shown in (60).

(58) MaxHeadμ[T] – Do not delete a tone from the head mora.

(59) a. MaxHeadμ[H] ≫ Max[L]
b. MaxHeadμ[L] ≫ Max[H]

(60) Loss of post-lexical low in non-final falling tone

<table>
<tr><td></td><td>H L
| |
μμ
V
n a ‘face’</td><td>MaxHeadμ[H]</td><td>*[TT]σ</td><td>Max[L]</td></tr>
<tr><td>a.</td><td>μμ
V
n a</td><td>*!</td><td></td><td>*</td></tr>
<tr><td>☞ b.</td><td>H
|
μμ
V
n a</td><td></td><td></td><td>*</td></tr>
<tr><td>c.</td><td>L
|
μμ
V
n a</td><td>*!</td><td></td><td></td></tr>
<tr><td>d.</td><td>H L
| |
μμ
V
n a</td><td></td><td>*!</td><td></td></tr>
</table>

The loss of the second tone does not induce re-alignment of the first tone or force tone spreading. Therefore, faithfulness to moraic associations (MaxLinkMora[T] , see (17) above) and a constraint against sharing tones between moras (*[μμ]T, see (23) above) must both outrank alignment:

(61) MaxLinkMora[T], *[μμ]T ≫ Align-R (post-lexical)

However, faithfulness to moraic association does not force two tones to surface faithfully in contours:

(62) *[TT]σ > > MaxLinkMora[T] (post-lexical)

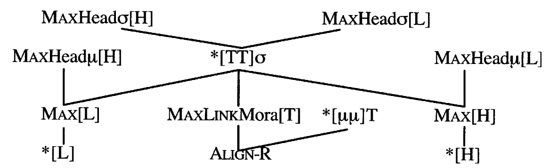
Loss of low in non-final post-lexical falling tone

<table>
<tr><th></th><th>H L
| |
μμ
V
n a 'face'</th><th>*[TT]σ</th><th>MaxLinkMora[T]</th><th>*[μμ]T</th><th>Align-R</th></tr>
<tr><td>☞ a.</td><td>H
|
μμ
V
n a</td><td></td><td>*</td><td></td><td>*</td></tr>
<tr><td>b.</td><td>H
/ \
μμ
V
n a</td><td></td><td>*</td><td>*!</td><td></td></tr>
<tr><td>c.</td><td>H
|
μμ
V
n a</td><td></td><td>**!</td><td></td><td></td></tr>
<tr><td>d.</td><td>H L
| |
μμ
V
n a</td><td>*!</td><td></td><td></td><td>*</td></tr>
</table>

Note that the rankings of the alignment constraint and constraints on faithfulness to moraic associations are reversed in the lexical and post-lexical components. In the lexical component, as was shown in (18) and (19) above, the optimal output for /HØ/ is ØH. In the post-lexical component, the high tone surfaces with its input moraic link intact, and both H0 (from HL) and 0H (from 0H) are allowed.

Combined with (54) above, the post-lexical tone grammar for Speaker 2 is:

(63)



There are only two crucial changes in ranking from the lexical grammar. In the lexical grammar, Max[H] and Max [L] outrank *[TT]σ, so that contour tones are allowed. In the post-lexical grammar, this ranking is reversed and contour tones are not allowed in non-prominent positions. (Post-lexical MaxHead constraints preserve contours in prominent syllables.) In the lexical grammar, Align-R outranks MaxLinkMora[T], so that single tones realign to the rightmost mora. In the post-lexical grammar, this ranking is reversed, and no realignment takes place.

5.3. *Post-lexical Grammar of Speaker 1*

The dialects of Speaker 1 and Speaker 2 differ only minimally with respect to tone. Speaker 2 simplifies both falling and rising tones; Speaker 1 simplifies only falling tones. Within the OT framework, one might expect this difference to be encoded in a minimal constraint ranking difference. In fact, a simple re-ranking of Max[H] above *[TT]σ results in the correct pattern.

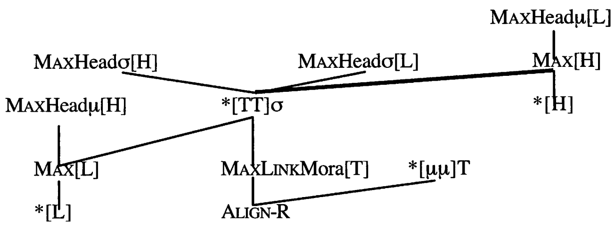
(64) No loss of high in non-final rising tone

<table>
<tr><td></td><td>L H
| |
μμ
V
n a 'thick'</td><td>Max[H]</td><td>*[TT]σ</td></tr>
<tr><td>a.</td><td>L
|
μμ
V
n a</td><td>*!</td><td></td></tr>
<tr><td>☞ b.</td><td>L H
| |
μμ
V
n a</td><td></td><td>*</td></tr>
</table>

The post-lexical tone grammar for Speaker 1 is given in (65). Note that the line in bold is the only difference from (63). With *[TT]σ ranked in between Max[H] and Max[L], the L of falling tones will be deleted, but the H of rising tones will not. Recall that ranking of Max[H] above Max[L] was argued for independently, above, to account for high tones surfacing on CVO syllables. That ranking is confirmed here.[21]

[21] As a final point, we note that the post-lexical tone realizations of both our speakers cast further doubt on the assertion of Zhang (2002) that falling pitch is always preferred in phonetically shorter syllables. The facts that both our speakers realized "falling" tones as phonetically rising in non-prominent position, and that Speaker 2 simplified falling but not rising tones, are exactly the opposite of what is predicted by Zhang's analysis.

(65)



6. Conclusions

What larger conclusions can we draw from this study? First, we have argued that Thai is a mora-timed language, which has a bimoraic requirement on stressed syllables. This is evidenced by segment distributional requirements, including the epenthesis of a glottal stop to augment underlyingly open syllables containing short vowels. In addition, we have shown that the vowel and coda consonant in CVVC syllables share a mora. This is supported by both vowel and consonant shortening in line with Broselow et al. (1997), as well as the distribution of tones in CVVO syllables. We have also proposed a new representation for Thai tones such that the mora is the tone-bearing unit and simple tones are aligned to the rightmost mora, while contour tones have one tone per mora. Further, we not only describe, but also explain, the relationship between moraically aligned phonological tones and pitch contours, demonstrating that quite complex pitch contours can be mapped onto very simple phonological representations.

Second, we have described and explained the puzzling distribution of tones in obstruent-final syllables. The markedness paradoxes associated with these syllables are readily accounted for by noting that coda obstruents in Thai have a glottal feature and that this feature induces a low tone. The fact that CVO syllables can also realize a high tone is the direct result of the ranking of independently motivated constraints, and it shows that the relationship between glottalized obstruents and low tones (in this language) is phonological, not merely phonetic.

Third, we have described and explained the differences between phrase-final and non-final contour tone realizations in connected speech. Using a combination of Stratal OT and Positional Faithfulness, prominent phrase-final contours at the post-lexical level are completely faithful to the output of the lexical level, while non-final contours may or may not simplify depending on the nature of the contour and the dialect. That is, although both of our speakers simplified post-lexical falling tones in non-final position, only one of them simplified rising tones. We show that association of tones to moras allows simplification of the contour tones without neutralizing contrasts with simple tones. High and low points at the end of the syllable indicate simple tones and in the middle of the syllable indicate contour tones. Further, we show that a dialect difference in the realization of non-final rising tones is the result of minimally different constraint rankings at the post-lexical level.

Fourth, although the phonetics of segment duration and pitch contours leads directly to particular phonological representations, we show that phonological constraints must in some cases operate at a level distinct from the phonetics. Lexical "high" tones are prohibited on CVVO syllables, yet in connected speech the "falling" tones on these syllables may in fact end at the top of the pitch range. To take another example, the prohibition on contours in the constraint against two tones per mora reflects a rejection of phonological, not phonetic, complexity. It is not the case that the phonologically short vowels in CVO syllables are simply of too short a duration to phonetically realize a contour tone. Though they are in fact very short (averaging as little as 80 ms according to Abramson (1962), and as short as 50 ms in our data for Speaker 2), a look at the pitch contours shows that phonetic timing is not the issue here. The high tones that appear on these syllables have a short, but fully realized, scooped contour – the same shape as appears on the longer vowels. On the other hand, the flat high of the "falling" contour is disallowed. Thus, our analysis has demonstrated the importance of careful phonetic study, yet we believe it also supports the independence of phonetics and phonology.

The research reported here has raised a number of issues regarding Thai phonetics and phonology that remain unresolved, and we look forward to addressing them in future work. We have touched in this paper on the issue of perceptual cues to the tonal contrasts of Thai, and perceptual testing of the cues proposed here is currently underway (Zsiga and Nitisaroj 2004). Further investigation of the interaction of stress and tone is needed, as well as exploration of how the representation of tonal contrasts might differ from dialect to dialect.

Finally, we have not had space to discuss what implications our analysis of Thai might have for other tone languages, but we suggest here a few areas for further research. We have argued that constraints on tone-syllable and tone-mora alignment can overcome the objection that moraic representations allow too many contrasts, continuing in the line of phonological reasoning that shifts the explanatory burden from representations to constraints. Nonetheless, we argue that the representations of tone-mora associations are crucial to explaining Thai phonetics and phonology. We have shown that, for Thai, quite complex tonal contours can be explained with quite simple combinations of tone features, without the need for a separate feature for register. We look forward in further research (Morén 2004) to exploring the implications of this mora-based and constraint-based approach for other Asian tone languages, particularly those that exhibit tone sandhi. We predict that the same set of constraints, ranked in slightly different ways, can express both the inventories and some of the sandhi patterns of other Asian languages. We also look forward to applying the method of relating phonological tones, their prosodic affiliations and their phonetic implementation argued here for Thai to other tone languages.

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Bruce Morén
Center for Advanced Study in Theoretical Linguistics
University of Tromsø
NO-9037 Tromsø
Norway
<bruce.moren@hum.uit.no>

Elizabeth Zsiga
Department of Linguistics
Box 571051
Georgetown University
Washington, DC 20057-1051
<zsigae@georgetown.edu>