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Tone, Production, Oto-Manguean

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The phonetics of moraic alignment in Yoloxóchitl Mixtec

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Abstract

This talk highlights recent research on the phonetics of tonal alignment in Yoloxóchitl Mixtec (YM). This language is notable for its large tonal inventory, where 20 tonal melodies contrast on monosyllabic words. The language's phonological structure strongly supports the alignment of tonal targets to moras, resulting in contrastive contour types even within a single syllable, e.g. /1.3/ vs. /13.3/. Patterns of phonetic tonal alignment were investigated. The alignment of non-glottalized tonal targets was examined with original field data collected by the authors from 10 speakers. Words varied by word type (monosyllabic, disyllabic) and tone. Both the phonological patterning of tone and patterns of phonetic alignment demonstrate a strong pattern of moraic tonal alignment in YM. The F_0 trajectories for bimoraic monosyllables closely match those of bimoraic disyllables. Moreover, in both word types, F_0 movement is restricted to only the mora with the associated target. Thus, a rising /1.3/ tone shows a marked delay in F_0 rise compared to the earlier rise observed with a /13.3/ tone. These findings support the notion that moras act as anchors for F_0 targets and trajectories within tone production. Such patterns stand in stark contrast to studies on tone languages for which the syllable is the unit of tonal alignment [1, 2, 3, 4]. Taken as a whole, this research expands our knowledge of tonal phonetics and challenges what we believe is possible in the tonal systems of human languages. As a more general perspective on tonal phonetics will emerge from the consideration of a typologically-diverse set of languages, this work also highlights the increasing relevance of laboratory methods in phonetic fieldwork.

Index Terms: Tone, Production, Oto-Manguean

1. Introduction

Though the study of tone in phonological theory has been heavily informed by work on a typologically-diverse set of languages, phonetic research on tone has remained largely focused on East and Southeast Asian languages. Absent from most phonetic discussions of tonal phenomena are the complex and unique patterns one observes in the tonal systems of the Oto-Manguean stock. These languages are not only known for their large tonal inventories and complex use of glottal features, but also for the myriad ways in which tone aligns with distinct prosodic structures and is associated with distinct morphological strata.

Yoloxóchitl Mixtec (YM henceforth), an Oto-Manguean language spoken in Mexico, is remarkable for its particularly large tonal inventory, with up to 20 tonal melodies possible on monosyllabic words and up to 28 on disyllabic words [5]. This large number of melodies can be simplified if we consider tone to be phonologically associated to moras, the typical tone-bearing units in the phonology of Mixtecan languages [6, 7]. Both distributional and morphological evidence support aligning tones to moras instead of syllables in YM. For instance, there is a contrast in both monosyllabic and disyllabic (both bimoraic) words between a /1.3/ rising contour, e.g. /ta^{1}a^3/ '*man*', vs. a /13.3/ rising contour, e.g. /nda^{13}a^3/ '*went up*.' However, it remains unclear how moraic alignment at the phonological level corresponds with the phonetic timing of tonal movements on YM words. Cross-linguistically, tonal F_0 targets are phonetically aligned to prosodic units of varying types. In Mandarin Chinese, for instance, the syllable serves as the unit of tonal F_0 alignment [1, 2, 3, 4]. In Thai, tones are aligned to moras [8, 9]. Yet, in languages with more complex tonal inventories and larger word types, it is less clear how tones are phonetically aligned to words. YM is one such language.

Patterns of phonetic tonal alignment were investigated in YM. The alignment of tonal targets was examined with original field data collected by the authors from 10 speakers. Four repetitions of 261 words produced in citation were examined per speaker, varying in word type (monosyllabic, disyllabic) and tone. Both the phonological patterning of tone and patterns of phonetic alignment demonstrate a strong pattern of moraic tonal alignment in YM. The F_0 trajectories for monosyllabic bimoraic words closely matches those of disyllabic bimoraic words. Moreover, in both word types, F_0 movement is restricted to only the mora with the associated target. Thus, a rising /1.3/ tone shows a marked delay in F_0 rise compared to the earlier rise observed with a /13.3/ tone. These findings support the notion that moras act as anchors for F_0 targets and trajectories within tone production, even within monosyllabic words.

2. Tonal alignment and Mixtec

2.1. Tonal alignment in phonology and phonetics

One of the most important advances within phonological theory has been the development of autosegmental-metrical (AM) theory [10, 11]. This theory provides a general framework for aligning tone and other suprasegmentals to prosodic units (onsets, rimes, moras, syllables, feet) found in speech. Within lexical tone languages, AM theory has been extremely useful in accounting for processes of tone sandhi and tonal association [12, 13, 14]. Phonological descriptions and analyses from a diverse set of language families have shown that lexical tone may be associated to syllables [15, 1, 16] (Sino-Tibetan, Oto-Manguean), moras [17, 18, 19, 7, 20, 21, 22] (Afro-Asiatic, Khoisan, Indo-European, Oto-Manguean), feet [23, 24] (Afro-

Asiatic), or even stems [25] (Oto-Manguean).

Despite the cross-linguistic phonological evidence for different tone-bearing units (TBUs), there is relatively little research examining phonetic timing in lexical tone production. Moreover, while one might assume parity between TBUs in phonological theory and the units used for phonetic timing, research on speech production has often found mismatches between traditional phonological representations and articulatory events in speech production, especially where gestural overlap occurs [26, 27, 28]. These observations emphasize the relevance of research on the phonetics of tonal alignment.

Phonetic research on Mandarin Chinese has observed that the syllable is the unit of tonal alignment [1, 2, 3, 4]. F_0 trajectories for lexical tones are aligned with the onset of the vowel [2] and F_0 offsets are aligned to the end of the syllable, regardless of whether a coda is present or not [1]. This insensitivity of Mandarin tone to the internal structure of the syllable has motivated models of tone production where F_0 trajectories are approximated on syllables [3, 4].

Yet, in other languages, there is evidence to consider the mora as the unit of phonetic tonal alignment. Thai possesses a contrast between short and long vowels [29] and there is evidence that listeners rely mainly on F_0 cues in the latter half of long vowels for perceiving tone [9]. While high tones are produced with lower F_0 onsets and low tones with higher F_0 onsets, listeners rely mainly on the cues later in the vowel for perceiving these tones. This observation has led researchers to theorize that the initial mora on long vowels for these tones is always tonally unspecified and mid tones have no tonal specification (ibid). By contrast, Thai contour tones are fully specified for tone on each mora (L+H, H+L) and listeners pay more at-

These findings support the idea that tone production targets the mora in Thai as listeners appear sensitive to different F_0 targets in the internal structure of the syllable.

In Kinyarwanda (Bantu), an earlier F0 peak is observed for H and HL tones on long vowels than for the LH tonal melody [30]. If one posits that H tones are only associated to the initial mora on long vowels, one not only captures this phonetic observation, but also a pattern of regressive H tone spreading. In this process, a H tone may spread onto the preceding long vowel, producing a rising tone when the preceding long vowel is low, e.g. LL+H > LH+H. This data not only shows the relevance of the mora to accounting for phonetic timing relations, but also to capturing phonological alternations. As is generally true, the most compelling evidence for a particular unit in phonological theory comes from multiple levels of linguistic structure. The behavior of tone in YM is no different in this regard, as there is compelling evidence for moras in morphophonological alternations involving tone as well as in its phonetic timing.

2.2. Yoloxóchitl Mixtec tone

Yoloxóchitl Mixtec [xty] is an Oto-Manguean language spoken in Guerrero, Mexico. Syllables are obligatorily open in the language and content words are minimally bimoraic, consisting of either a consonant followed by a long vowel, e.g. /ñũ^{3}ũ^{2}/ '*town*,' or two syllables each consisting of shorter vowels, e.g. /nda^{1}Ba^{1}/ '*undivided branch*.' Both types of words may be contrastively glottalized, e.g. /ñũP^{3}ũ^{2}/ '*fire*' and /ndaP^{1}Ba^{1}/ '*to be turned off*.' Glottalization is an orthogonal, foot-level feature with respect to the tonal contrasts in the language. While larger monomorphemic roots occur, this bimoraic structure is the most common shape of lexical stems in the language and corresponds to what is commonly known as the Mixtec *couplet* [31, 6] or foot [22]. The first phonological description of the language appears in [5]. The current work differs slightly from this previous work as only four (and not five) tonal levels are posited to exist. More extensive phonetic descriptions of the consonant and vowel systems in YM are forthcoming [32, 33].

Up to 20 surface tonal melodies are possible on monosyllabic words and 28 in disyllabic words. However, by dividing these words into two moras, one observes a significant reduction in the tonal inventory. For instance, in monosyllabic words, the initial mora may consist of tones /1, 3, 4, 13, and 14/ and the final mora may consist of tones /1, 2, 3, 4, 13, 14, 24, 42/. Thus, one can reduce the tonal inventory to four levels /1, 2, 3, 4/, three rises /13, 14, 24/, and one fall /42/ for such words. Table 1 shows the possible tonal combinations in monosyllables. Note that while the tonal contours on monosyllables are less convincing as to the presence of four tone heights, data (not shown) from disyllabic words shows this pattern more convincingly. Four possible falling melodies, /4.3/, /4.2/, /4.1/, and /3.2/, may occur on such words.

Table 1: *Tonal melodies in monosyllabic words*

	$T_{\mu 1}$				
$T_{\mu 2}$	1	3	4	13	14
1	nda^{1}a^{1} '*flat*'	X	X	X	X
2	X	nda^{3}a^{2} '*sloping*'	nda^{4}a^{2} '*where*'	kwe^{13}e^{2} '*linger*'	ndi^{14}i^{2} '*pink*'
3	ta^{1}a^{3} '*man*'	Sa^{3}a^{3} '*fast*'	X	nda^{13}a^{3} '*went up*'	Sa^{14}a^{3} '*new*'
4	ndo^{1}o^{4} '*sugarcane*'	nde^{3}e^{4} '*strong*'	nda^{4}a^{4} '*black*'	tu^{13}u^{4} '*stripped*'	X
13	X	X	nde^{4}e^{13} '*they.enter*'	X X	ndo^{14}o^{13} '*to not stay*'
		'*is peeling*'		'*is not peeling*'	
24	X	X	ka^{4}a^{24} '*slips*'	X	ka^{14}a^{24} '*does not slip*'
42	X	ñũ^{3}ũ^{42}	X	X	X

Despite a reduction of the tonal inventory in terms of moras, there exists a surface contrast in YM between rising tonal melodies which are simply combinations of two separate level tones on separate moras, e.g. 1.4, and contour tones which surface on individual moras, e.g. 14.3. Furthermore, note that not all combinations are possible. Rising tones on the second mora only occur after tones /4/ and /14/ on the initial mora. Finally, not all tones have the same morphological status; most words with tone /13/ in the initial mora are completive verb stems where a low tone /1/ is fused to the leftmost mora, e.g. /nda^{3}a^{3}/ '*to go up*' vs. /nda^{13}a^{3}/ '*went up*.' Most words with tone /14/ in the initial mora are verb stems where negation is marked with a low tone /1/ fused to the leftmost mora, e.g. /ka^{4}a^{24}/ '*slips*' vs. /ka^{14}a^{24}/ '*does not slip*.'

While a moraic alignment of tone in YM provides a more economical analysis of the tonal inventory, reducing 20 melodies to different combinations of eight tones, it also provides an more elegant analysis of the tonal morphology. For instance, habitual verbs are formed by replacing the tone on the initial mora with tone /4/. Transitive verbs may be formed by replacing the tone on the initial mora of verbs with tone /1.4/ with /3/, e.g. /kwi^{1}i^{4}/ '*to be peeled*' vs. /kwi^{3}i^{4}/ '*to peel*'. These alternations target the tone on the initial mora of the word regardless of word size (monosyllabic, disyllabic). Data showing these alternations is given in Table 2.

The mora is useful in providing a more economical description of the tonal inventory in YM and for capturing tonal alter-

Table 2: *Habitual and transitive verb alternations in YM*

Irrealis verb		Habitual verb	
a. Sa^{1}a^1	'*to arrive*'	Sa^{4}a^1	'*to be arriving*'
b. kã^{3}ã^2	'*to perforate*'	kã^{4}ã^2	'*to be perforating*'
c. ka^{1}Ba^1	'*to spin*'	ka^{4}Ba^1	'*to be spinning*'
d. ka^{3}tSi^2	'*to say*'	ka^{4}tSi^2	'*to be saying*'
Intransitive verb		**Transitive verb**	
e. kwi^{1}i^4	'*to be peeled*'	kwi^{3}i^4	'*to peel (tr)*'
f. kũ^{1}ũ^4	'*to be ground*'	kũ^{3}ũ^4	'*to grind*'
g. tu^{1}Si^4	'*to be cut up*'	tu^{3}Si^4	'*to cut up*'
h. ta^{1}Si^4	'*to be untied*'	ta^{3}Si^4	'*to untie*'

nations, but it remains unclear how such complex sequences are tonal events are timed in speech production. Furthermore, one might hypothesize that the replacement of tones shown in the morphological process in Table 2 simply involves changing the initial F_0 target in the word without any specific reference to prosodic structure within the bimoraic foot. One way to examine this possibility versus the moraic hypothesis is to examine the relative timing of F_0 trajectories on words of different tonal melodies and prosodic shapes.

3. Tone production experiment

3.1. Method

To examine the production of tone in YM words, the authors constructed a list of words to be produced in citation/isolation. Several examples (between 2-7) of words containing the same tonal melody and word size (monosyllable vs. disyllable) were included. Multiple examples were sought so as to balance words with respect to onset consonant voicing. While a balanced set of glottalized and non-glottalized tokens were collected, only the non-glottalized data were analyzed in this study. Thus, from a total of 251 words that were recorded, 164 were analyzed here. All words were repeated six times across two separate sessions by 10 native speakers (6 male, 4 female). From these recording sessions, only the initial two repetitions were chosen (4 repetitions per speaker). A total of 6,560 word tokens were analyzed for the purposes of this study. The recording took place in a quiet room in the town of San Luis Acatlán, which is adjacent to Yoloxóchitl. All words were elicited via a verbal prompt in YM by the third author, who is a native speaker.

Subsequent to recording, all words were manually segmented by Leandro DiDomenico, a graduate student at Université Lyon 2, and checked by the first author. The F_0 contours from these vowels were extracted using Voicesauce, a program for analyzing voice quality and F_0 in Matlab [34]. In order to compare F_0 contours on monosyllables and disyllables, four time-normalized F_0 values were extracted from each vowel of the disyllabic words for a total of eight F_0 values. These eight values were then compared to eight values extracted from the monosyllabic words. The implicit assumption in this method is that one can divide a single vowel into two durational parts, each of which roughly corresponds to a different mora, and compare these F_0 contours to those found in separate vowels/moras in disyllabic words. While this may be a simplistic assumption, it follows if we assume that the mora is not only a unit of phonological timing, but also of phonetic alignment. F_0 was extracted for each vowel using the *Straight* method [35]. A by-speaker z-score normalization F_0 was applied to all data prior to analysis. From these data, F_0 extrema were calculated along with the locations of the extrema.

The data was analyzed using two sets of linear mixed effects models [36]. In the first model, z-score F_0 was treated as the dependent variable while Tone, Word size, and Time (with 8 levels, recentered) were treated as independent variables. This model simply examines how unmodified F_0 values vary with respect to the independent variables and was applied to the entire data set. In the second series of models, each of the factors, F_0 minimum, F_0 maximum, the location of the F_0 minimum, and the location of the F_0 maximum, were treated as separate dependent variables while Tone and Word size were treated as independent variables. These models are designed to evaluate specifically whether word size contributes to a change in the F_0 extrema or the locations of such extrema. Such an analysis is necessary to examine F_0 alignment. These models were applied separately to each tonal melody type (see below). For all models, significance was assessed via model comparison using the anova() function and the χ^2 test.

3.2. General Results

In the first set of models, there was a significant main effect of tone. The model containing tone as a predictor was significantly better than one excluding it (χ^2 = 10544, $p < .001$; AIC=75360 vs. AIC=64928). The same model comparison found Time to be a significant predictor (χ^2 = 4973, $p < .001$; AIC=69841 vs. AIC=64928). Word size was also significant, though to a much smaller degree than either Time or Tone (χ^2 = 675, $p < .001$; AIC=65543 vs. AIC=64928). However, the effect of word size on F_0 manifested itself in different ways depending on the tonal melody. There was a significant two-way interaction between Tone and Word size (χ^2 = 86.1, $p < .001$; AIC=65545 vs. AIC=65547) and a significant three-way interaction between Tone, Word size, and Time (χ^2 = 587.2, $p < .001$; AIC=65487 vs. AIC=64928). Yet, once we exclude these interactions from the mixed effects model, we find no contribution of Word size (χ^2 = 1.9, $p = .4$; AIC=65543 vs. AIC=65545). Thus, we can conclude that there is no general effect of word size on F_0 contours, but one restricted to certain tonal melodies. These word size effects by tonal melody are investigated in the following sections.

While many of the tonal melodies which surface on monosyllabic words are equivalent to those on disyllabic words, certain patterns are more frequent. We restricted our analysis to fifteen tonal melodies which surface on both word types, organized by section here: level melodies (/1.1/, /3.3/, /4.4/), rising melodies (/1.3/, /1.4/, /3.4/, /13.3/, /13.4/), falling melodies (/4.2/, /3.2/), concave melodies (/4.13/, /4.14/, /4.24/), and double rising melodies (/14.14/, /14.13/). The statistical models in these sections evaluate F_0 extrema and their locations. The locations of F_0 minima and maxima by Word size for all tonal melodies are shown in Figures 1 and 2.

3.2.1. Level tones

Level tones are shown in Figure 3. YM contrasts three level tonal melodies and each differs significantly in F_0 level. The low, /1.1/ tonal melody, is typified with a falling F_0 contour. There was a small, but significant effect of Word size on F_0 maxima in level tones (χ^2 = 9.0, $p < .05$). In particular, while tone /4.4/ is produced with a slight rise in F_0 in monosyllabic words, it is flatter in disyllabic words with a higher F_0 in the initial syllable. A significant effect of Word size on the location of F_0 maxima was also found (χ^2 = 42.0, $p < .001$). Tonal

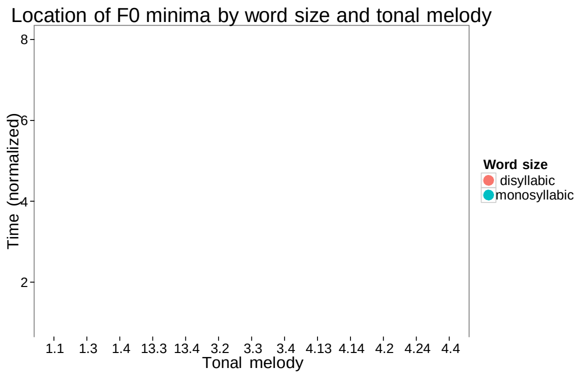

Figure 1: F_0 *minima by word size and tonal melody*

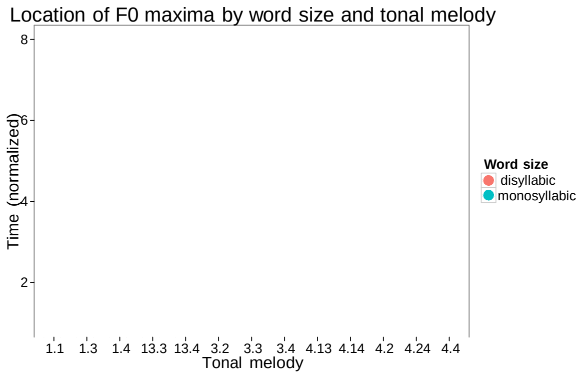

Figure 2: F_0 *maxima by word size and tonal melody*

melody /1.1/ was realized with a later F_0 maximum in disyllabic words since it was produced with a slightly concave contour on the initial syllable. A significant effect of Word size on the location of F_0 minima was also found (χ^2 = 20.0, p < .001). The tonal melody /1.1/ often reached an earlier minimum in disyllabic than in monosyllabic words. Each of these effects are shown in Figures 1 and 2. Tones /3.3/ and /4.4/ did not differ in the alignment of F_0 extrema, though each tonal melody was level. There was no significant effect of Word size on F_0 minima for level tones.

3.2.2. Rising tones

Five types of rising tonal melodies occur in both monosyllabic and disyllabic words: /1.3/, /1.4/, /3.4/, /13.3/, and /13.4/.[1] The first three rises are *simple* rising contours and are shown in Figure 4. The latter two rising tonal melodies are *complex* rising contours. A comparison between the simple rising contour /1.3/ and the complex contour /13.3/ is shown in Figure 5. The simple rises /1.3/ and /1.4/ are characterized with a slight fall over the first half of the vowel in monosyllabic words. This fall is also seen for these tones in disyllabic words. However, it is not observed with the complex rises /13.3/ and /13.4/. Here, the initial half of the vowel in both monosyllabic and disyllabic words has a rising F_0 contour. These differences between each pair of the tonal melodies, /1.3 vs. 13.3/ and /1.4 vs. 13.4/, is shown through an examination of the data in Figure 1. The

[1] An additional rising melody, /14.4/, is found only in disyllabic words.

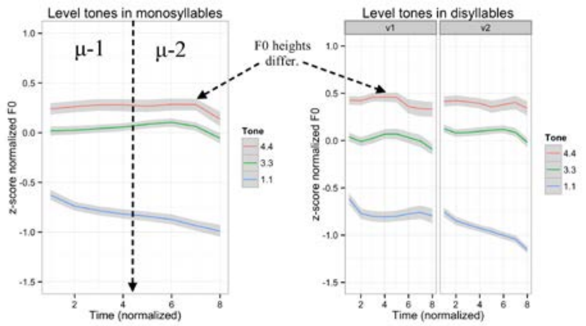

Figure 3: *Level tones by word size*

F_0 minima for melodies /13.3/ and /13.4/ occur earlier in both monosyllabic (Time = 1.4 and 1.6, respectively) and disyllabic words (Time=3.2 and 3.4, respectively) than the F_0 minima for melodies /1.3/ and /1.4/ in monosyllabic (Time = 2.7 and 2.9, respectively) and disyllabic words (Time = 5.0 and 4.7, respectively).

There is a significant effect of Word size on the location of F_0 minima (χ^2 = 54.0, p < .001). The minima for all rising tones occurred later in disyllabic words than in monosyllabic words. Despite these differences in F_0 minima location, note that the minima for all complex rises remained in the initial half of the vowel in monosyllabic words or the initial vowel in disyllabic words. The same was not true for the minima observed with simple rises, which were produced either late in the initial syllable/mora or early in the final syllable/mora. Though F_0 minima were aligned earlier for complex rises than in the simple rises, the minima for all rising tones remain in what corresponds to the initial mora of the word. In addition, the rise in F_0 for the simple rises is restricted to either the second syllable of disyllabic words or the second half of the vowel in monosyllabic words. F_0 raising for all simple rises only occurs in the final mora, regardless of whether the word is monosyllabic or disyllabic.

There was also a significant effect of Word size on the location of F_0 maxima (χ^2 = 39.3, p < .001). F_0 maxima occur earlier in disyllabic words for all rises than they do in monosyllabic words. This effect may arise due to word duration, as disyllabic words are typically longer than monosyllabic words, despite both typically having an equal number of moras. There was no effect of Word size on F_0 maxima values, but a significant effect of Word size on F_0 minima values (χ^2 = 21.1, p < .001). The tonal melody /13.4/ was realized with a much higher minimum in monosyllabic words than in disyllabic words.

3.2.3. Falling tones

YM contrasts only two falling tonal melodies; /4.2/ and /3.2/. While a falling contour may surface on the final mora in disyllabic and monosyllabic words, e.g. /1.42/ and /3.42/, there are no complex falling melodies of the shape */4.42/ nor */3.32/ that are akin to the complex rises. The two falling tonal melodies are shown in Figure 6.

There was a significant main effect of Word size on F_0 maxima (χ^2 = 18.5, p < .001). For tonal melody /4.2/, disyllabic words were produced with slightly higher F_0 maximum in the initial vowel. Significant main effects of Word size on F_0 maximum location (χ^2 = 27.1, p < .001) and minimum location (χ^2 = 26.9, p < .001). The higher F_0 maximum may result from

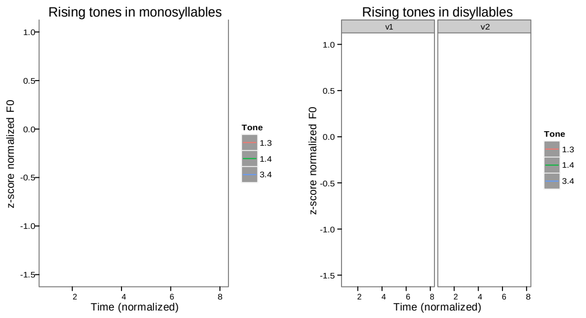

Figure 4: *Simple rising tones by word size*

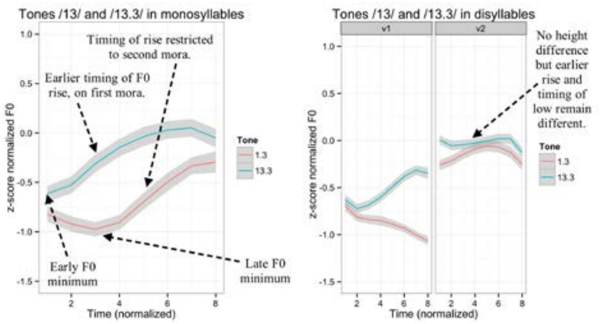

Figure 5: *Comparison between simple and complex rising tonal melodies by word size*

the differences in alignment observed with Word size. Falling melodies in disyllabic words were produced with a rise in F_0 in the initial syllable prior to the onset of the fall, but no such rise is found in monosyllabic words. As a result, the F_0 maxima occur later in the initial mora of disyllabic words than in monosyllabic words (see Figure 2). However, F_0 minima occur slightly earlier in disyllabic words than in monosyllabic words (see Figure 1).

3.2.4. Concave tones

Three types of concave tonal melodies occur in bimoraic words in YM: /4.14, 4.13, 4.24/. Such melodies are phonologically analyzed as sequences of tone /4/ and a subsequent rising tone on a separate mora. Each of the concave tonal melodies are shown in Figure 7. Since certain concave melodies possess potentially two distinct maxima, e.g. /4.14, 4.24/, a statistic examining F_0 maxima is not appropriate here. Only the F_0 minima are considered.

No main effects of word size on F_0 minima or minima locations were observed for concave tonal melodies. As seen in Figure 1, the minima for all such melodies were consistently located early in the second half of the vowel in monosyllabic words or early in the second vowel in disyllabic words (in the second mora). Since the minima always occurred in what corresponds to the second mora in such words, the rising portions of all melodies were also restricted to this domain. The realization of concave melodies differed by word size insofar as there was a clear transition between the initial tone level /4/ in monosyllabic words and the subsequent rise (producing a falling+rising contour), but the melodies did not differ in terms of alignment.

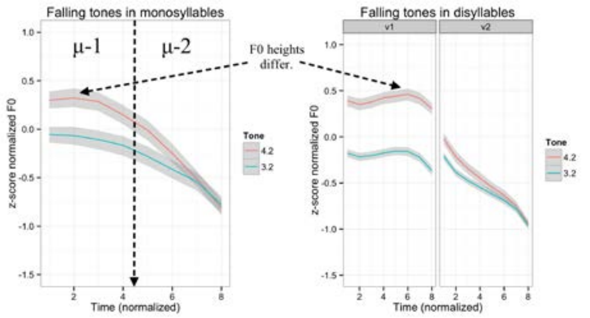

Figure 6: *Falling tones by word size*

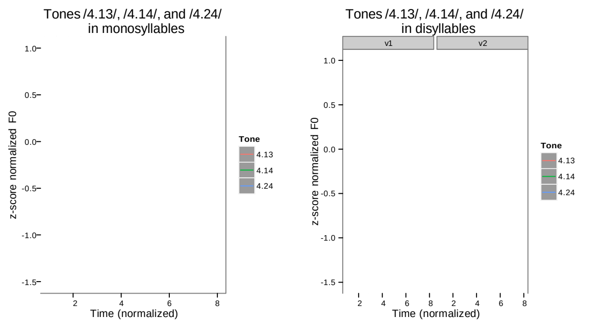

Figure 7: *Concave tonal melodies by word size*

3.2.5. Double rising tones

There are two types of double rising tonal melodies that surface on monosyllabic and disyllabic words in YM: /14.14/ and /14.13/.[2] Each of these melodies only surfaces on negated forms of verbs. Both tonal melodies are shown in Figure 8. As tonal melody /14.14/ contains multiple F_0 extrema (maxima and minima), it was not analyzed with respect to F_0 extrema. Only the maximum for melody /14.13/ was considered. No effect of Word size on F_0 maximum was observed for this tone, but there was a significant main effect of Word size on F_0 maximum location (χ^2 = 24.3, p < .001). The F_0 maximum for this tone is earlier in monosyllabic words (Time = 2.9) than in disyllabic words (Time = 4.7).

The F_0 contours for both tonal melodies share certain characteristics. First, the initial rise is restricted to the initial half of the vowel in monosyllabic words and the first vowel in disyllabic words. The subsequent minima and rises are restricted to the latter half of the vowel in monosyllabic words and the final vowel in disyllabic words. The earlier F_0 maxima observed in monosyllabic words may result from a physical necessity of the speaker to descend to the second F_0 minimum early enough in the latter half of the vowel. This particular hypothesis would closely fit with the view that F_0 extrema are aligned within moras.

4. Discussion

4.1. Moraic alignment

The data here demonstrate the careful timing of F_0 in the complex tonal melodies found in YM. Across the tonal melody

[2] Tonal melody /14.24/ surfaces only in monosyllabic words.

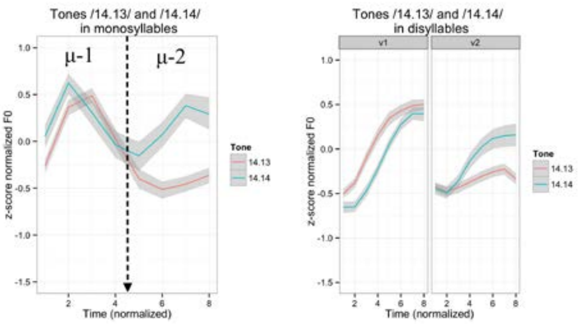

Figure 8: *Double rising tonal melodies by word size*

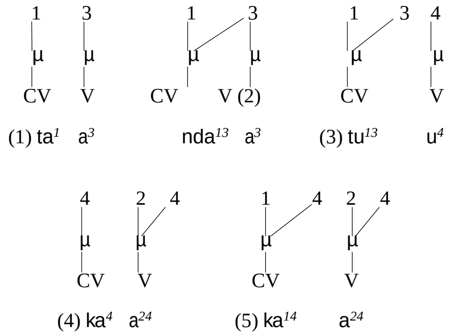

Figure 9: *Phonological and phonetic alignment of YM tones*

types, significant effects of Word size on the timing of F_0 extrema were found. Yet, despite such differences, extrema remained almost entirely aligned within the duration corresponding to the mora to which the tone is phonologically associated. In simple rising tones, there is a marked delay in F_0 rise compared to complex rising tones and there is a slight fall in F_0 prior to the rise. One result of the later timing of the F_0 minimum is that the F_0 rise remains restricted the second mora of the word. A similar pattern is observed with the concave tones, where the F_0 minima and the subsequent rises consistently occurred early within the second mora of the word. Finally, the double rising melodies were also typified by the restriction of each pair of extrema (minima + maxima) to separate moras regardless of the size of the word.

For the simple rising melodies, there is no a priori reason why the demands of F_0 production would favor delaying the production of a rising contour on monosyllabic words. Such a finding mirrors the observations made in the production of Thai high or rising tones, where a similar delay in minima is observed [9]. A parallel observation occurs with the concave contours where the minimum location is delayed to the second half of the vowel in monosyllabic words or the final vowel of disyllabic words. Moreover, the similarities in alignment across words of varying syllable length (but not moraic length) are not predicted in theories of tone production where F_0 extrema are simply associated to syllables [1, 3, 4] or where the timing of tonal melodies are insensitive to moraic structure [37]. The observations here support the idea that tone is not only phonologically-associated to moras in YM, but phonetically aligned to them as well.

4.2. The phonetic typology of tonal systems

Contrasts between tonal melodies such as /1.3/ and /13.3/, as shown in Figure 5, are typologically unique and demonstrate an additional exception to the claim that lexical tone may not be contrastively aligned *within* a syllable [38, 14]. The presence of this contrast supports recent work showing that falling contours may be contrastively aligned in Dinka (Nilotic), where both an early-aligned and late-aligned fall occur [39]. However, the current work differs from this research in terms of how such contrasts are phonologically represented. In certain dialects of Dinka, the contrastively-aligned falling tones surface equally on short, long, and overlong vowels. This implies that the TBU for Dinka is the syllable, not the mora. Contrastive alignment in Dinka is modelled in terms of features, where tone may be specified as [± late aligned]. However, this alternative to prosodically-based alignment is unnecessary for the YM data. Apart from the phonetic data, there is ample phonological evidence that the tones on individual moras may be targeted by morphological processes and none of the complex tonal melodies observed in bimoraic stems are possible in monomoraic morphemes, most of which are function words.

The analysis here favors the alignment of not only tone levels to individual moras, but also tonal contours. The representation of different tonal types in AM terms is given in Figure 9 for several of the words from Table 1. Tones are prosodically aligned to moras and up to two distinct tones may be associated to a given mora. Each tone in a simple rises, as in (1), is associated with a single mora, while tones in complex rises, as in (2) and (3), have a more complex association. Both contain multiple tone to mora association, but multiple mora to tone association is possible in (2). Patterns such as those in (4) and (5) demonstrate that both the initial and final moras in monosyllabic words may be associated with contours. The structure shown in (5) also demonstrates an additional typological exception. Contour tones are typically either analyzed as sequences of level tones, as in many Bantu languages, or as undecomposable units, as in many Sino-Tibetan languages [40]. Where the two co-occur in a language, one[1] usually observes combinations similar to that shown in (3) or (4). A series of sequential rises or falls, each of which are unanalyzeable units but sequence like combinations of levels, has not previously been observed.

5. Conclusions

The data from the complex tonal melodies in YM demonstrate the relevance of the mora as a unit of both phonological timing and phonetic alignment. Moraic structure is not simply assumed to account for distributional differences and alternations with tone, but it is supported by the phonetic timing data. Oto-Manguean languages are characterized by an exceptional complexity not just in terms of tonal inventory size, but in how such tones are timed in relation to word structure. While YM possesses a complex inventory regardless of one's analysis, the set of possible melodies on monosyllabic words is much reduced by considering the mora as the TBU. Typological considerations into the size and complexity of tonal inventories need to look carefully at the nature of the TBU in particular languages, lest we mischaracterize apparent (or hidden) complexity in tonal systems. As a more general perspective on tonal phonetics will emerge from the consideration of a typologically-diverse set of languages, this work also highlights the increasing relevance of laboratory methods in phonetic fieldwork.

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7. References

[1] Y. Xu, "Consistency of tone-syllable alignment across different syllable structures and speaking rates," *Phonetica*, vol. 55, pp. 179–203, 1998.

[2] M. Gao, "Mandarin tones: An articulatory phonology account," Ph.D. dissertation, Yale University, 2008.

[3] S. Prom-on, Y. Xu, and B. Thipakorn, "Modeling tone and intonation in Mandarin and English as a process of target approximation," *Journal of the Acoustical Society of America*, vol. 125, no. 1, pp. 405–424, 2009.

[4] Y. Xu and S. Prom-on, "Toward invariant functional representations of variable surface fundamental frequency contours: Synthesizing speech melody via model-based stochastic learning," *Speech Communication*, vol. 57, pp. 181–208, 2014.

[5] R. Castillo García, "Descripción fonológica, segmental, y tonal del Mixteco de Yoloxóchitl, Guerrero," Master's thesis, Centro de Investigaciones y Estudios Superiores en Antropología Social (CIESAS), México, D.F., 2007.

[6] M. Macaulay, *A Grammar of Chalcatongo Mixtec*, ser. University of California Publications in Linguistics, L. Hinton, L. M. Hyman, P. Munro, W. Shipley, and S. Thompson, Eds. University of California Press, 1996, vol. 127.

[7] J. P. Daly and L. M. Hyman, "On the representation of tone in Peñoles Mixtec," *International Journal of American Linguistics*, vol. 73, no. 2, pp. 165–207, 2007.

[8] B. Morén and E. C. Zsiga, "The Lexical and Post-Lexical Phonology of Thai Tones," *Natural Language and Linguistic Theory*, vol. 24, pp. 113–178, 2006.

[9] E. Zsiga and R. Nitisaroj, "Tone features, tone perception, and peak alignment in Thai," *Language and Speech*, vol. 50, pp. 343–383, 2007.

[10] J. Goldsmith, "Autosegmental Phonology," Ph.D. dissertation, MIT, 1976.

[11] ——, *Autosegmental and metrical phonology*. Oxford: Blackwell, 1990.

[12] L. M. Hyman, "Universals of tone rules: 30 years later," in *Tones and Tunes*, T. Riad and C. Gussenhoven, Eds. Mouton de Gruyter, 2007, vol. 1: Typological Studies in Word and Sentence Prosody.

[13] M. Yip, "Tone," in *The Cambridge Handbook of Phonology*, P. DeLacy, Ed. Cambridge University Press, 2007, ch. 10, pp. 229–252.

[14] ——, *Tone*, ser. Cambridge Textbooks in Linguistics. Cambridge University Press, 2002.

[15] S. Duanmu, "Rime length, stress, and association domains," *Journal of East Asian Linguistics*, vol. 2, no. 1, pp. 1–44, 1993.

[16] R. Castillo Martínez, "El sistema tonal del chinanteco de San Juan Quiotepec, Oaxaca," Master's thesis, Centro de Investigaciones y Estudios Superiores en Antropología Social (CIESAS), 2011.

[17] A. Amha, "Tone-accent and prosodic domains in Wolaitta," *Studies in African Linguistics*, vol. 25, no. 2, pp. 111–138, 1996.

[18] A. Miller-Ockhuizen, "Reduplication in Ju|'hoansi: Tone Determines Weight," in *Proceedings of NELS 29*, M. Hirotani, Ed. Amherst: University of Massachusetts Occasional Papers in Linguistics, 1999.

[19] C. Gussenhoven and P. Van Der Vliet, "The phonology of tone and intonation in the Dutch dialect of Venlo," *Journal of Linguistics*, vol. 35, pp. 99–135, 1999.

[20] C. T. DiCanio, "The Phonetics and Phonology of San Martín Itunyoso Trique," Ph.D. dissertation, University of California, Berkeley, 2008.

[21] M. E. Chávez Peón, "The interaction of metrical structure, tone, and phonation types in Quiaviní Zapotec," Ph.D. dissertation, The University of British Columbia, 2010.

[22] I. McKendry, "Tonal Association, Prominence, and Prosodic Structure in South-eastern Nochixtlán Mixtec," Ph.D. dissertation, University of Edinburgh, 2013.

[23] W. Leben, "Tonal feet and the adaptation of English borrowings into Hausa," *Studies in African Linguistics*, vol. 25, pp. 139–154, 1996.

[24] M. Pearce, "The interaction between metrical structure and tone in Kera," *Phonology*, vol. 23, pp. 259–286, 2006.

[25] E. Cruz, "Phonology, tone, and the functions of tone in San Juan Quiahije Chatino," Ph.D. dissertation, University of Texas at Austin, 2011.

[26] C. Browman and L. Goldstein, "Tiers in articulatory phonology, with some implications for casual speech," in *Papers in laboratory phonology 1: between the grammar and the physics of speech*, J. Kingston and M. E. Beckman, Eds. Cambridge University Press, 1990, pp. 341–376.

[27] L. Goldstein and C. A. Fowler, "Articulatory Phonology: A phonology for public language use," in *Phonetics and Phonology in Language Comprehension and Production: Differences and Similarities*, N. O. Schiller and A. S. Meyer, Eds. Mouton de Gruyter, 2003.

[28] I. Chitoran, L. Goldstein, and D. Byrd, "Gestural overlap and recoverability: Articulatory evidence from Georgian," in *Papers in laboratory phonology 7*, C. Gussenhoven and N. Warner, Eds. Berlin, New York: Mouton de Gruyter, 2002.

[29] A. S. Abramson, "The vowels and tones of Standard Thai: Acoustical measurments and experiments," *International Journal of American Linguistics*, vol. 28, no. 2, pp. Indiana University Research Center in Anthroplogy, Folklore, and Linguistics: Bloomington, Publication 20, 1962.

[30] S. Myers, "F_0 Timing in Kinyarwanda," *Phonetica*, vol. 60, pp. 71–97, 2003.

[31] L. Hinton, "An Accentual Analysis of Tone in Chalcatongo Mixtec," in *Papers from the American Indian Languages Conferences Held at the University of California, Santa Cruz*, ser. Occasional Papers on Linguistics, No.16, J. E. Redden, Ed. Carbondale: Southern Illinois University, 1991, pp. 173–182.

[32] C. DiCanio, C. Zhang, D. H. Whalen, J. D. Amith, and R. Castillo García, "Phonetic structure in Yoloxóchitl Mixtec consonants," submitted.

[33] C. DiCanio, H. Nam, J. D. Amith, R. Castillo García, and D. H. Whalen, "Vowel variability in elicited versus spontaneous speech: evidence from Mixtec," submitted.

[34] Y.-L. Shue, P. Keating, and C. Vicenik, "VOICESAUCE: A program for voice analysis [computer program]," *Journal of the Acoustical Society of America*, vol. 126, no. 2221(A), 2009.

[35] H. Kawahara, A. de Cheveigné, and R. D. Patterson, "An Instantaneous-Frequency-Based Pitch Extraction Method for High-Quality Speech Transformation: Revised Tempo in the Straight Suite," in *Proceedings of the 5^{th} International Conference on Spoken Language Processing*, 1998.

[36] R. H. Baayen, *Analyzing Linguistic Data: A Practical Introduction to Statistics Using R*. Cambridge University Press, 353 pages, 2008.

[37] J. Zhang, "The role of contrast-specific and language-specific phonetics in contour tone distribution," in *Phonetically-based Phonology*, B. Hayes, R. Kirchner, R. M. Kirchner, and D. Steriade, Eds. Cambridge University Press, 2004.

[38] D. Silverman, "Tone sandhi in Comaltepec Chinantec," *Language*, vol. 73, pp. 473–492, 1997.

[39] B. Remijsen, "Tonal alignment is contrastive in falling contours in Dinka," *Language*, vol. 89, no. 2, pp. 297–327, 2013.

[40] M. Yip, "Contour tones," *Phonology*, vol. 6, no. 1, pp. 149–174, 1989.