# TRIQUI TONAL COARTICULATION AND CONTRAST PRESERVATION IN TONAL PHONOLOGY*

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Tonal languages vary substantially in the degree in which coarticulation occurs across word boundaries. In languages like Mandarin, coarticulation is strong and results in extensive variation in how tones are produced (Xu, 1994). In languages like Thai, coarticulation is noticeably weaker and does not result in the same degree of tonal overlap (Gandour, Tumtavitikul, and Satthamnuwong, 1999). Just what accounts for such differences? The current study examines how tones are coarticulated in Itunyoso Triqui (IT), an Oto-Manguean language with nine lexical tones, across different contexts and speech rates. The findings show that contour tones influence the production of adjacent tones significantly more than level tones do, often resulting in tonal assimilation. Though, the degree of assimilation across contexts was relatively small in comparison to previous work on tonal coarticulation. Tonal dissimilation between the highest and lowest tones in the experiment and $F_0$ range expansion during faster speech rate were also observed. These findings suggest that IT speakers actively preserve tonal contrasts in their language in conditions where one would anticipate the greatest mechanical overlap between tones. The ramifications of this research are discussed in relation to the literature on tone production and perception. This research predicts that tonal languages which more heavily weigh $F_0$ height as a tonal cue undergo less coarticulatory variation than those which weigh $F_0$ slope more heavily.

**Keywords:** tone, coarticulation, Oto-Manguean, speech rate

## Introduction

In the initial stage of describing a tone language, one typically examines how each lexical tone is produced in isolated words. The purpose of this approach is to carefully investigate how previously established tonal categories are distinguished from one another acoustically. Such descriptions often produce a clear, maximally-dispersed tonal space which is considered to reflect the general acoustic distinctions among tones. Though useful, these idealized $F_0$ trajectories may differ dramatically from tonal patterns embedded in larger speech contexts and produced at different speech rates. This lack of correspondence is not limited to tones which undergo phonological alternations (sandhi) in context, but may occur equally strongly as the result of phonetic processes of tonal coarticulation.

Just what coarticulatory factors account for this lack of correspondence is an active topic of phonetic research. Like the production of consonants and vowels, the type of the context in which a tone is produced can dramatically influence how it is produced, altering $F_0$ slope, level, and even direction (Xu, 1994). Moreover, changes in speech rate can alter how much such contextual factors play a role in tone production and the overall range in which tones are produced (Gandour et al., 1999). Yet, unlike segmental coarticulation, tone production is constrained due to the reliance on a single articulator, the larynx, for the production of each pitch target. So while $F_0$ trajectories may blend or shift between adjacent tones, one may not produce distinct tonal targets simultaneously as one often observes within segmental coarticulation.[1]

The focus of the current work is to explore how contextual factors and speech rate influence the production of Itunyoso Triqui tones. Itunyoso Triqui (IT, henceforth) is a complex tone language spoken

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[1]Compare this to the in-phase coupling of onsets and vowels in speech articulation (Browman and Goldstein, 2000; Nam and Saltzman, 2003) and to the more extensive examples of overlap that may occur with distinct articulators like the lips and tongue tip.

in Oaxaca, Mexico and has been the focus of both descriptive and experimental work on tone (DiCanio, 2008, 2010, 2012a,b, 2014). To examine the research questions here, natural sentences were constructed with a controlled sequence of tonal combinations. These sentences were spoken at two speech rates by eight speakers. The results show that contour tones induce greater coarticulatory influence on adjacent tonal targets than level tones do. An increase in speech rate also results in an expansion of speaker's $F_0$ ranges as speakers seek to actively maintain tonal contrasts in IT.

This research is relevant for both models of speech production and historical sound change. The production of speech involves the careful coordination and timing of different articulators; and the factors influencing tonal overlap and coarticulation are similar to those influencing segmental overlap and coarticulation. However, research on speech articulation has focused almost exclusively on the major speech articulators in the oral cavity, such as the tongue and lips. From an articulatory perspective, we still understand little of how laryngeal gestures and $F_0$ targets fit within a general theory of speech production.[2] As approximately 50-60% of the languages of the world have lexical tone or phonation contrasts (Yip, 2002), any general model of speech production should include an account of how lexical tones are coordinated.

Furthermore, it is broadly understood that synchronic phonological alternations can evolve from tendencies observed in the coarticulation of speech sounds (Ohala, 2001; Beddor, 2009). In a parallel way, tone sandhi, tonal alternations, and distributional asymmetries in tonal phonology may have their roots in processes of tonal coarticulation (Zhang and Lai, 2010). Two adjacent tones, $T_a$ and $T_b$, may influence each other where they overlap at their temporal boundaries to such an extent that, diachronically, a change in tonal category occurs. Yet, just which tone exerts a stronger coarticulatory influence on the other in such pairs? Is the pattern anticipatory or perseveratory? and what predicts the directionality? These questions are addressed in the current study.

# 1 Background

## *1.1 Tonal Coarticulation*

Studies on tone-tone coarticulation focus on three major patterns: the magnitude of contextual effects on tone production (in $F_0$ and in time), whether these effects are assimilatory or dissimilatory, and the directionality of the effects on the adjacent syllable (anticipatory/perseveratory). The magnitude of coarticulatory effects varies across languages. In Mandarin Chinese, tonal contexts which involve mismatches between offset-onset targets, e.g. high $F_0$ offset + low $F_0$ onset, may substantially perturb the $F_0$ contours on adjacent tones (Xu, 1994). This perturbation is so great in Mandarin that listeners perform at near chance level in identifying the tone of excised coarticulated $F_0$ contours (ibid). In contexts such as these, coarticulation is nearly neutralizing.

Figure 1 shows that a substantial degree of levelling occurs when contour tones are produced in mismatched contexts. This is exaggerated with faster speech rate. By contrast, the same tones produced in a compatible context, e.g. high $F_0$ offset + high $F_0$ onset, maintain their $F_0$ trajectory. Mandarin is not like all tone languages though. Thai tones produced at different speech rates in stressed and unstressed syllables mostly retain their shape and do not seem to undergo the same degree of levelling that one observes in Mandarin (Gandour et al., 1999). Thus, while tones in many lexical tone languages undergo contextual variation as a function of the adjacent tones, e.g. in Malaysian Hokkein, Thai, Vietnamese, and Taiwanese (Chang and Hsieh, 2012; Gandour, Potisuk, and Dechongkit, 1994; Brunelle, 2009; Peng, 1997), languages vary substantially in the degree in which $F_0$ trajectories are permitted to vary.

[2]Though see some recent work on this topic (Gao, 2008; Mücke, Grice, Becker, and Hermes, 2009; Mücke, Nam, Hermes, and Goldstein, 2012; Katsika, Krivokapić, Mooshammer, Tiede, and Goldstein, 2014).

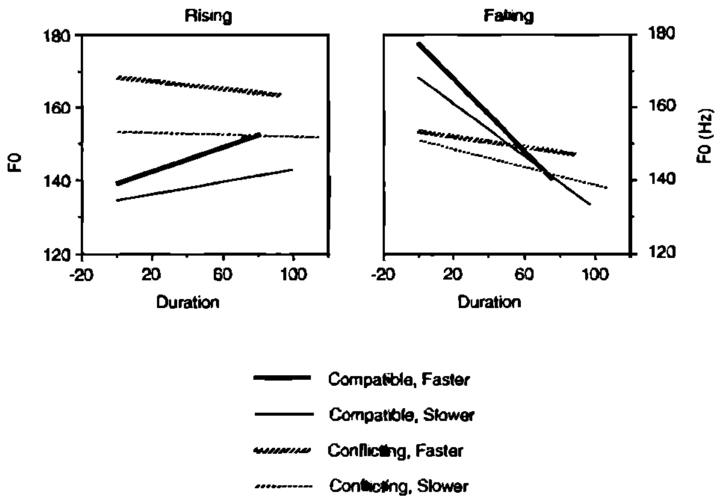


**Figure 1:** Mandarin rising and falling tones in "conflicting" (mismatched) and "compatible" contexts at two speech rates (from Xu (1994)).

Though the magnitude of the such effects varies, research on different languages has concluded that tonal coarticulation is primarily assimilatory in nature. In other words, adjacent tonal targets tend to become more similar to one another. However, there is one exception to this trend: in many languages, high tones dissimilate when they precede a low tone target. Anticipatory dissimilation of this sort occurs in Malaysian Hokkien (Chang and Hsieh, 2012), Taiwanese (Peng, 1997), and Mandarin Chinese (Xu, 1997). This pattern is striking because perseveratory effects seem to be more common in tonal coarticulation (Xu, 1994; Brunelle, 2009; Chang and Hsieh, 2012). Anticipatory patterns tend to be shorter in duration and smaller in magnitude. Most languages are argued to show little anticipatory coarticulation. Tianjin Chinese seems to be the only language investigated in the literature showing slightly greater anticipatory than perseveratory tonal coarticulation (Zhang and Liu, 2011). However, tonal coarticulation has been investigated in relatively few languages to date.

As contour tones are dynamic, one predicts that they will undergo greater coarticulatory perturbation than level tones due to greater temporal demands at faster speech rates. Within the more general literature on pitch production, researchers have shown that increased speech rate also causes tonal target undershoot (Xu and Sun, 2002). However, there is an ongoing debate in the literature as to whether pitch accents (and tones) show consistent alignment across speech rates. In languages like English and Mandarin Chinese, there is evidence for consistent alignment (Ladd, Faulkner, Faulkner, and Schepman, 1999; Xu, 1998). In Peninsular Spanish, pitch accent alignment varies more substantially with rate (Prieto and Torreira, 2007).

The research here is an extension of previous work on tonal coarticulation. As languages vary substantially in both the degree of tonal coarticulation and in its directionality, investigating how it works in IT is of typological-empirical interest. This is especially noteworthy since there has been no investigation of tonal coarticulation in an Oto-Manguean language to date. Oto-Manguean languages, and IT more specifically, possess unique phonologies and complex tonal systems not found in the more commonly-studied lexical tone languages. Just how tonal coarticulation unfolds in a language with nine lexical tones and final stress is of comparative phonetic interest.

### *1.2 Itunyoso Triqui Tone*

Itunyoso Triqui is an Oto-Manguean languages spoken in Oaxaca, Mexico. Like many Oto-Manguean languages, it is heavily tonal. There are nine lexical tone contrasts in the language (DiCanio, 2008, 2010). This includes four level tones: /1/, /2/, /3/, /4/, where /4/ indicates the highest level tone, and five contour tones: /43/, /32/, /31/, /13/, /45/. Each tone may occur in monosyllabic or polysyllabic words, but there are distributional restrictions as to what type of syllable each tone may occur in. While non-final syllables in Triqui words are always open, final syllables (of which monosyllabic words are one type) may be either open or closed with a laryngeal coda /ʔ, ɦ/. No contour tone surfaces preceding a glottal stop coda; only level tones may precede a glottal stop. Rising tones /13/ and /45/ each only surface on syllables with a breathy coda, /ɦ/. Tone /31/ never surfaces on syllables with a breathy coda; it only surfaces on open syllables. The breathy coda has the phonetic effect of lowering $F_0$ on the latter half of the rime, while the glottal stop /ʔ/ lowers $F_0$ only slightly or inconsistently on the preceding vowel (DiCanio, 2012a). Table 1 shows the lexical tone contrasts on monosyllabic words in Triqui.

**Table 1:** Tones on Monosyllables by rime type

| Tone | CV | Gloss | CVʔ | Gloss | CVɦ | Gloss |
|---|---|---|---|---|---|---|
| /4/ | $\beta$ːe$^4$ | *hair* | nːiʔ$^4$ | *our mother* | βeɦ$^4$ | *beat.3sg (intr.)* |
| /3/ | nːe$^3$ | *plow* | nːeʔ$^3$ | *straw rope* | nːeɦ$^3$ | *dream* |
| /2/ | nːe$^2$ | *to lie (tr.)* | nːiʔ$^2$ | *smelly* | βːeɦ$^2$ | *cave* |
| /1/ | nːe$^1$ | *naked* | ʔniʔ$^1$ | *be.salty* | cnãɦ$^1$ | *brother (voc.)* |
| /45/ | * | * | * | * | βːeɦ$^{35}$ | *straw mat* |
| /13/ | * | * | * | * | keɦ$^{13}$ | *barely* |
| /43/ | li$^{43}$ | *small* | * | * | nːãɦ$^{43}$ | *mother (voc.)* |
| /32/ | nːe$^{32}$ | *water* | * | * | nːãɦ$^{32}$ | *cigarette* |
| /31/ | nːe$^{31}$ | *meat* | * | * | * | * |

In addition to lexical tone, IT possesses stem-final stress. Final syllables are phonetically longer than non-final syllables and more phonological contrasts are realized on final syllables as well (DiCanio, 2008, 2010). While IT possesses a complex set of morphological tonal alternations which mark verbal aspect and personal clitics (DiCanio, submitted, no date) , there is no purely phonologically-conditioned tone sandhi across words.[3] As a result, any phonetic differences among identical tones across contexts result from processes of tonal coarticulation.

Figure 2 shows IT tone production in monosyllabic words. Previous work on the production of IT tone shows that each of the phonologically level tones is produced with a level $F_0$ across the vowel duration (DiCanio, 2008, 2012a). Each of the falling tones also differ in $F_0$ height and, for tone /31/, in slope as well. The rising tones differ in $F_0$ height, but have similar overall shapes.

## 2 Method

### *2.1 Stimuli and Speakers*

The data consisted of a series of 16 natural three-word sentences produced by eight native Triqui speakers (4 male, 4 female), repeated five times each at two different speech rates (normal and fast). In these sentences, the initial and final words were disyllabic and matched for one of four tonal melodies: /2.2/, /3.3/, /3.32/,

[3] All Triqui variants are similar in this regard (Hollenbach, 1977, 1984).

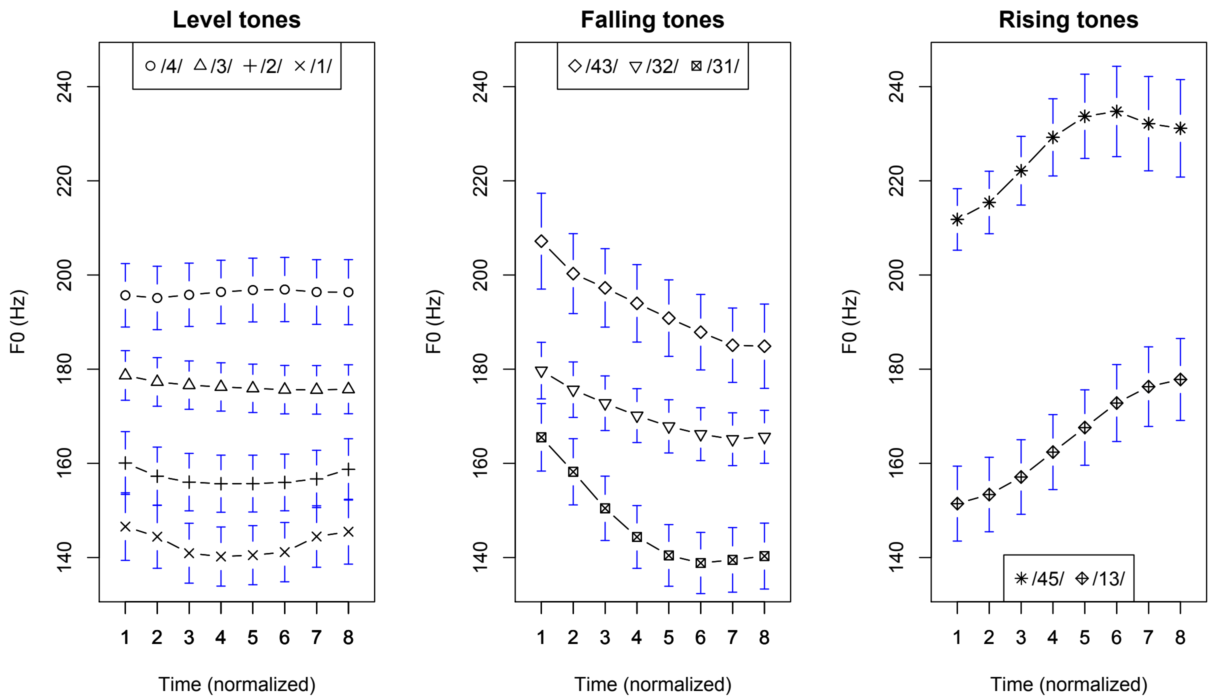


**Figure 2:** The time-normalized production of IT tones averaged across six speakers. The data here was taken from monosyllabic words in carrier phrases in DiCanio (2008, 2012a). The error bars here reflect p value of 0.05.

/3.45/. The medial word consisted of a monosyllabic word with one of four tones: /2/, /4/, /43/, /45/. For instance, in the the sentence /ri$^{3}$jũ$^{32}$ sĩh$^{45}$ re$^{3}$to$^{32}$/, 'The man measures the blanket.', the initial and final words have tonal melody /3.32/ while the medial word has tone /45/. The syntactic structure of all sentences was Verb+Subject+Modifier. A total of 160 sentences per speaker were recorded for a total of 1280 sentences. The elicited sentences are given in Table 3 in the appendix. Speakers first repeated all sentences at a normal, comfortable speech rate, and then were asked to repeat them at a faster rate.

The acoustic data was recorded using an H4N-Zoom digital recorder and a Nady HM-10 head-mounted microphone. Elicitation was carried out in Triqui by the author and a native consultant. All speakers were familiarized with the sentences prior to recording and were told to repeat either the author or the native consultant's production. Recording took place in a quiet room in the town of San Martín Itunyoso in Oaxaca, Mexico. All eight participants were native speakers of Itunyoso Trique without a history of hearing or speech disorders. Speakers were compensated for their participation.

### *2.2 Analysis method*

All data was hand-labelled using Praat (Boersma and Weenink, 2013). $F_0$ data across each segment duration was extracted using the sub-harmonic to harmonic ratio threshold method in Voicesauce (Shue, Keating, and Vicenik, 2009). This method worked better in $F_0$ estimation than alternate methods which resulted in $F_0$ doubling or halving in the speech of certain speakers. As we were interested in the transition between syllables across words, a large number of $F_0$ samples (20) were extracted from each segment interval. The $F_0$ values were converted into log scores and a by-speaker z-score normalization was applied. Note that we are not primarily interested in the average $F_0$ difference among IT tones here, as the basic phonetic differences among the tones have been established, but rather in how much each tone varies as a function of tonal context and speech rate. Thus, the dependent variable was tonal variability, or the a measure of how much a speaker's tone production varied from their centroid for that tone as a function of context and rate. This measure has the advantage of also centering the data around a mean value; those contexts which do not significantly influence tone production should be close to the mean.

Statistical models were built for each tone in each position (12 models). Three independent factors were evaluated within the statistical models: time, rate, and the adjacent tonal context. For the variable of time, each of the $F_0$ samples were given a value corresponding to the normalized time and recentered for statistical analysis. As we are primarily interested in how the entire tonal shape varies as a function of context and not short portions of transition into and out of the tone, only the medial 50% of all vowels were evaluated in the model. Speaker was treated as a random intercept. The effects of predictor variables were evaluated by using an analysis of variance on the linear mixed effects model. This model relies on the Satterthwaite method to approximate for degrees of freedom via the *lmerTest* (Kuznetsova, Brockhoff, and Christensen, 2013) and reports both an F statistic and p values, but only a lower bound on degrees a freedom. There is currently no way to approximate the upper bound on degrees of freedom for linear mixed effects models (Baayen, 2008). All statistics were calculated using R (R Development Core Team, 2013).

## 3 Results

As several factors were evaluated here, the results section is divided into three parts. The first part examines tonal coarticulation on each of the three words in the stimuli, the second evaluates the effect of speech rate on tone production, and the third shows how duration varied by tone and rate.

### *3.1 Tonal coarticulation by word*

#### 3.1.1 Anticipatory effects on the leftmost word

The first context considered here is the production of tones on the final syllable of the leftmost word. Anticipatory effects on the final syllable of these words are shown in Figures 3 and 4. The $F_0$ contours in each figure are tracks of the same tone (on the same word) as a function of the tone on the following word. On the left of Figure 3, we observe variation in the production of tone /2/ as a function of context. This tone was raised significantly preceding contour tones /43/ ($t[3465] = -3.9$, $p < .001$) and /45/ ($t[3465] = 8.4$, $p < .001$). When this tone was produced before level tones /2/ and /4/, it did not significantly differ from its centroid.

On the right of Figure 3, we observe variation in the production of tone /3/ as a function of context, most notably a substantial $F_0$ lowering when it preceded tone /43/. However, on closer inspection, it turned out that certain speakers produced this tone with a /Vɦ/ rime (indicating $1^{st}$ person) in this context instead of with the expected /Vː/ rime. Breathiness on the rime has the effect of causing $F_0$ lowering here, as discussed in DiCanio (2012a). For statistical analysis, all tone /3/ productions were excluded when they preceded tone /43/. With this context excluded, only the following tone /45/ significantly shifted the production of tone /3/ from its centroid ($t[2660] = 8.3$, $p < .001$). Preceding this tone, the $F_0$ of tone /3/ was slightly raised. Note that the anticipatory effects on these level tones were all assimilatory and occurred only before contour tones.

Turning to the contour tones on the leftmost word in Figure 4, we observe what appears to be rather little overall variation in the production of tone /32/ as a function of the following context. Tone /32/ varied significantly from its centroid when preceding tone /4/ ($t[3283] = -4.3$, $p < .001$), tone /43/ ($t[3283] = -7.4$, $p < .001$), and tone /45/ ($t[3283] = -9.5$, $p < .001$). The overall level of the contour was lowered preceding these tones, resulting in a small degree of tonal dissimilation. On the right in Figure 4, we observe more

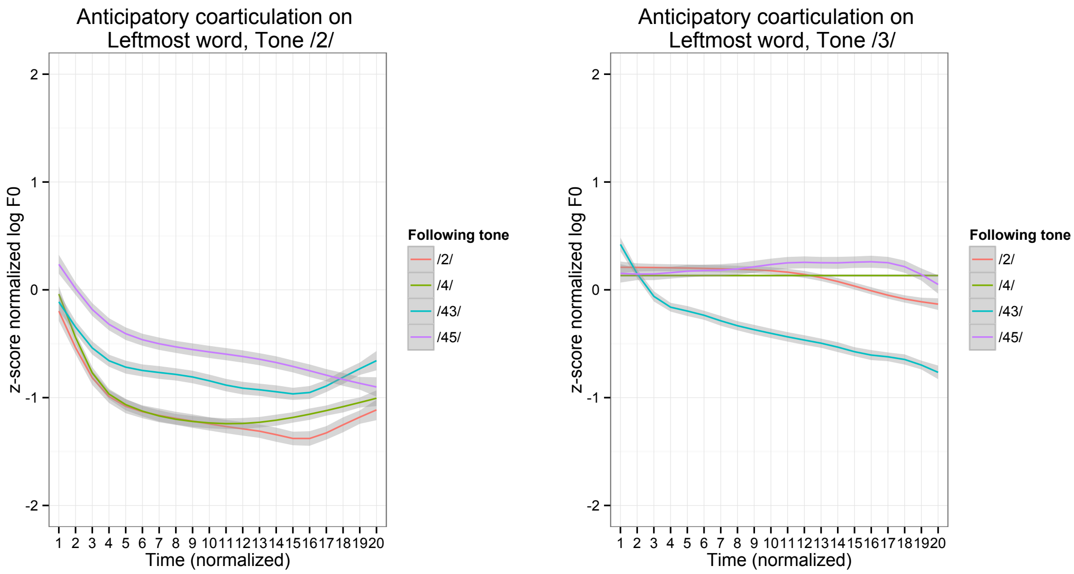


**Figure 3:** Anticipatory coarticulation on level tones on the initial word. Grey error bars reflect standard error.

noticeable effects of context on tone production. Tone /45/ is significantly raised preceding tone /43/ (t[3355] = -2.5, $p < .05$) and tone /45/ (t[3355] = 3.8, $p < .001$), resulting in tonal dissimilation. This tone rises when preceding level tones, but is relatively level when preceding contours.

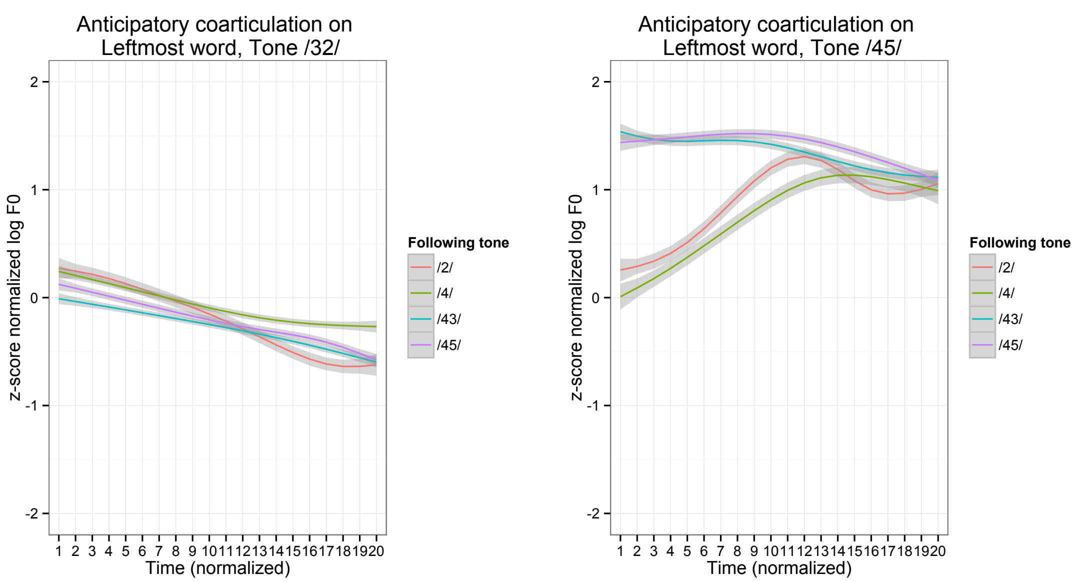


**Figure 4:** Anticipatory coarticulation on contour tones on the initial word. Grey error bars reflect standard error.

### 3.1.2 Effects on the medial word

Unlike the initial word in each stimulus sentence, the medial words were monosyllabic. Coarticulatory effects on this syllable are shown in Figures 5 and 6. Rather than apply default contrast coding, the factor of context was centered at tone /3/, which reflects the tone closest to the center of each speaker's pitch range. On the left of Figure 5, we observe a significant effect of tonal contexts /2.2/ and /3.32/ on the production of tone /2/ ($t[3408] = 3.9$, $p < .001$; $t[3408] = 10.0$, $p < .001$). Though subtle, this tone was slightly raised in the context of these adjacent tones. However, a more striking effect was observed with this tone when it occurred in the context of tones /3.45/. Here, tone /2/ was significantly lowered ($t[3408] = 8.0$, $p < .001$). This latter process reflects a dissimilatory pattern whereby this lower tone is lowered even further when in the context of adjacent high rising tones. On the right of Figure 5, one does not observe much of a notable influence of adjacent tones on monosyllables with tone /4/, though significant effects of adjacent tones /3.32/ and /3.45/ were found ($t[3464] = 4.1$, $p < .001$; $t[3464] = 5.2$, $p < .001$). While the tonal trajectories averaged across speakers do not reveal much variability here, a closer inspection of by-speaker tone production shows that several speakers produced lowered tone /4/ variants in the context of adjacent tone /3.32/ and raised variants in the context of adjacent tone /3.45/. Both patterns are assimilatory in nature.

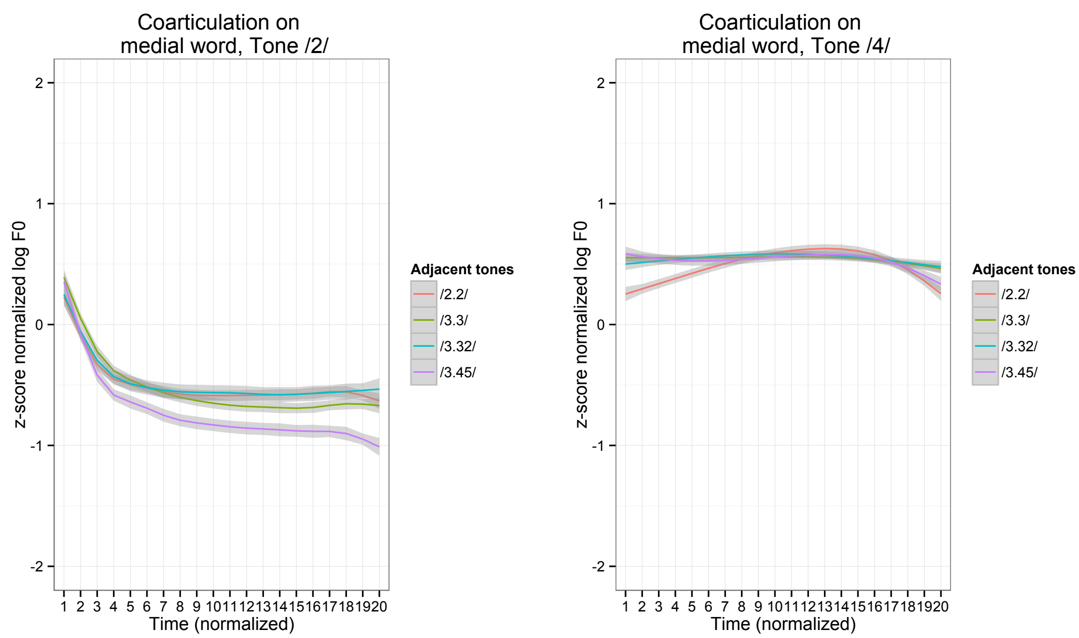


**Figure 5:** Coarticulation on level tones in medial words. Grey error bars reflect standard error.

Turning to the coarticulatory effects on medial contour tones, we observe a similar, but stronger effect of adjacent tone /3.32/ on tone /43/ as we observed above on tone /4/. Tone /43/ was significantly lowered in this context ($t[3452] = 7.3$, $p < .001$). A small, but significant effect of adjacent tone /3.45/ on tone /43/ was also found ($t[3452] = -2.3$, $p < .05$). Tone 43/ was slightly raised in this context. Similar to the effects on tone /4/ above, both patterns were assimilatory. On the right of Figure 6, we observe significant effects of each adjacent tone on the production of tone /45/. The strongest effects were observed when tones /2.2/ and /3.32/ were adjacent to this tone ($t[3529] = -8.5$, $p < .001$; $t[3529] = -8.4$, $p < .001$). Tone /45/ was significantly raised when these tones were adjacent. Each of these patterns were dissimilatory in nature, as the tones were lower in comparison to tone /45/. However, a smaller, but significant assimilatory effect was found in the context of tone /3.45/ ($t[3529] = -3.6$, $p < .001$). Tone /45/ was raised in this context.

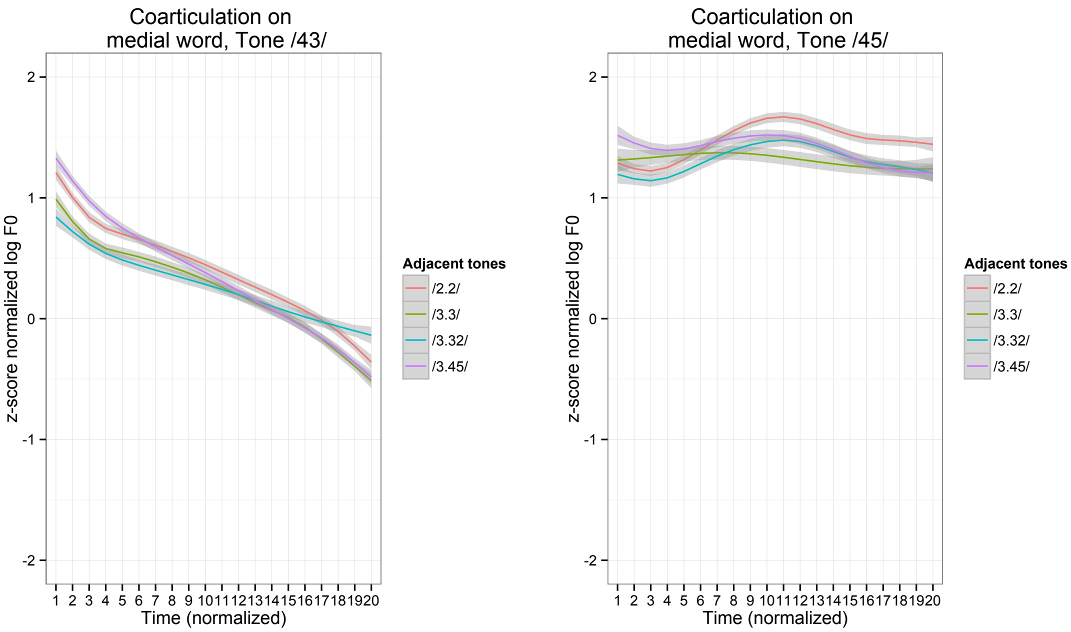


**Figure 6:** Coarticulation on contour tones in medial words. Grey error bars reflect standard error.

### 3.1.3 Effects on the final word

In the previous two sections, only word-final, stressed syllables were analyzed. The effects on the initial, unstressed syllable of the final word are analyzed here. Contour tones do not surface on non-final syllables in IT and while tone is contrastive in these syllables, tone /3/ is a common default tone. As a result, the tones on the initial syllables for three of the four tonal melodies on the rightmost word were identical, e.g. /2.2, 3.32, 3.3, 3.45/. While these non-final tones are phonological identical, they belong on different word-tonal melodies. Thus, they were analyzed as separate tone targets for statistical purposes here.

Figure 7 shows the tonal trajectories for words with a level tonal melody, /2.2/, /3.3/. At first glance, we observe what appears to be a great deal of variation in how tones /2/ and /3/ were produced. These two tones appear to overlap to a substantial degree. On the left of Figure 7, we observe a significant effect of the preceding tone /45/ target on tonal melody /2.2/ ($t[3487] = 7.7$, $p < .001$). Tone /2/ underwent assimilatory raising in this context. No other carryover effects were significant for this tonal melody. On the right of Figure 7, we observe significant effects of the preceding tone /45/ on tone /3/ ($t[3506] = 4.2$, $p < .001$) and of the preceding tone /4/ on tone /3/ ($t[3506] = -3.4$, $p < .001$). Tone /3/ underwent assimilatory raising in these contexts.

Figure 8 shows the tonal trajectories for words with a contour tonal melody, /3.32/, /3.45/. Observing tone /3/ the left, we observe small, but significant effects of the preceding tones /45/ and /43/ ($t[3394] = 2.8$, $p < .01$; $t[3394] = 2.3$, $p < .05$). Tone /3/ underwent assimilatory raising when preceded by tone /45/ but lowering when preceded by tone /43/. This lowering may be considered assimilatory, however, as the falling trajectory of tone /43/ may continue onto the following syllable. Observing tone /3/ on the right, we observe stronger effects of the preceding context. There was a significant effect of tone /45/ on tone /3/ here ($t[3476] = -5.6$, $p < .001$). Tone /3/ underwent assimilatory tonal raising here. A significant effect of tone /43/ on tone /3/ was also found ($t[3476] = -7.9$, $p < .001$). As with tonal melody /3.32/, tone /3/ underwent assimilatory lowering in this context.

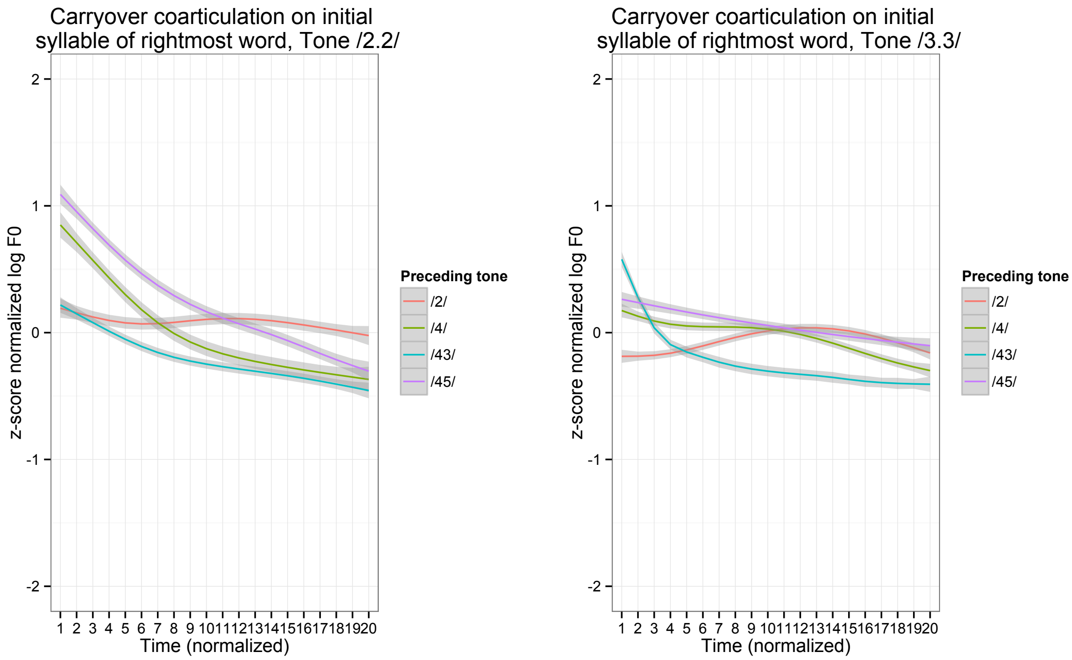


**Figure 7:** Coarticulation on non-final syllables in final words containing a level tonal melody. Grey error bars reflect standard error.

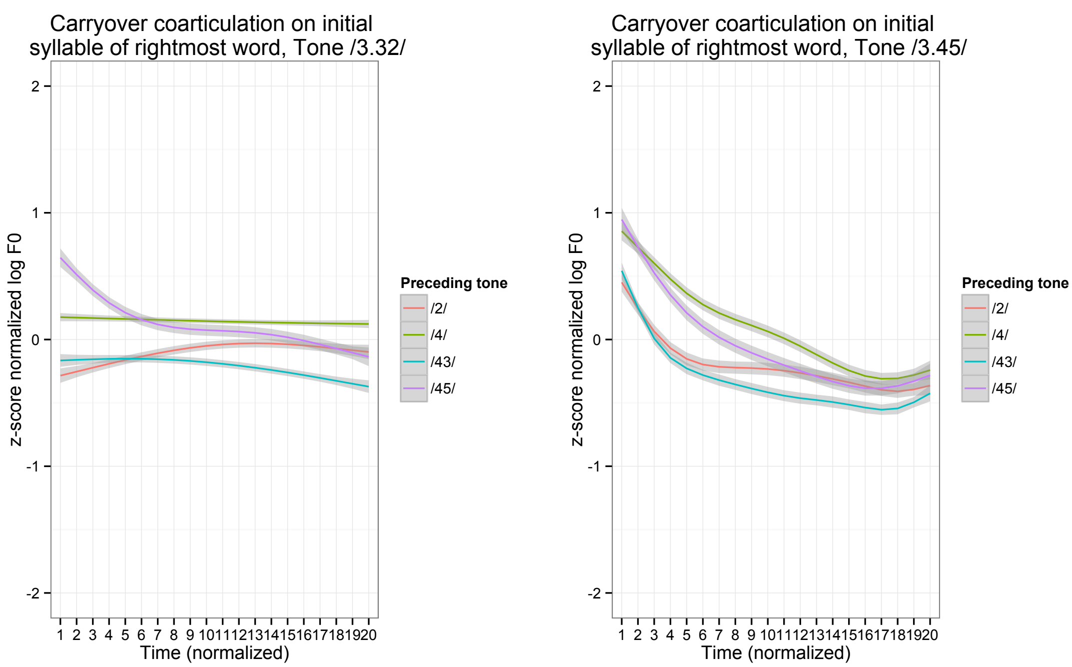


**Figure 8:** Coarticulation on non-final syllables in final words containing a contour tonal melody. Grey error bars reflect standard error.

### 3.1.4 Summary of contextual effects

Table 2 provides a summary of the effects above. On the final syllable of the initial word, we observe anticipatory effects of both following contour tones, /43/ and /45/. By contrast, anticipatory effects before level tone /4/ occurred only in one tonal context. A similar pattern is found in the medial monosyllabic word. Here, robust coarticulatory effects were observed for each tones when they occurred between contour tones /3.32/ and /3.45/, but fewer effects when tones occurred between level tones. In the initial syllable of the final word, carryover effects are strongest when the preceding tone contained a contour as well.

**Table 2:** Contextual effects by tone and word. The effects here are read as "an effect of tone /A/ on /B/".

| | Tones influencing production | | |
|---|---|---|---|
| Initial Word | /4/ on /3.32/ | /43/ on /2.2, 3.3, 3.45/ | /45/ on /2.2, 3.32, 3.45/ |
| Medial Word | /2.2/ on /2, 45/ | /3.32/ on /2, 4, 43, 45/ | /3.45/ on /2, 4, 43, 45/ |
| Final Word | /4/ on /3.3/ | /43/ on /3.32, 3.45/ | /45/ on /2.2, 3.3, 3.32, 3.45/ |

Most of the effects observed here were assimilatory in nature. However, a few dissimilatory patterns stand out. Dissimilation occurred mostly in the medial, monosyllabic word and always involved the highest and lowest tones examined in the study. Tone /2/ lowered between adjacent words with tone /3.45/ and, vice-versa, tone /45/ raised between adjacent words with tones /2.2/ and /3.32/. Dissimilation never occurred with tones close to one another in the $F_0$ range. The significance of this finding is discussed in §4.

### *3.2 The effects of speech rate on tone production*

Figure 9 shows the speech rate for each speaker across the rate conditions. An average speech rate, measured in syllables per second, was extracted across each set of repetitions of a stimulus sentence. A linear mixed effects model was constructed with observed rate as the dependent variable, rate condition as the independent variable, and speaker as a random variable. All speakers produced sentences more quickly in the fast speech rate condition than in the normal speech rate condition and there was a strong effect of condition on observed speech rate ($t[247] = -21.0$, $p < .001$). The average ratio between normal and fast speech was 1:1.26 across speakers. Male speakers (BCM, JLG, RDM, WCM) produced a faster speech rate on average than female speakers did.

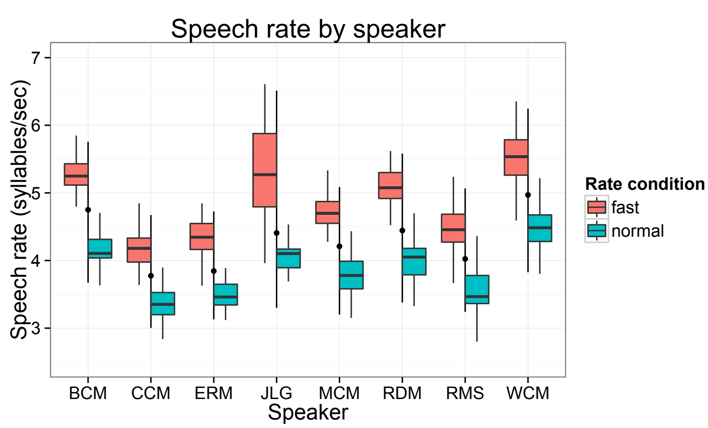


**Figure 9**

Figure 10 shows the influence of speech rate on tone production in the initial and medial words in the stimulus sentences. On the whole, speakers expanded their $F_0$ ranges with faster speech rate. This effect was robust across speakers and genders. The range expansion was stronger for tones in the upper $F_0$ range and, as a result, influenced higher tones more than lower tones. Within both the initial and medial words, we observe that tone /45/ has a higher variant when produced at a faster speech rate than at a normal speech rate. There was a significant effect of rate on the production of this tone in the medial word ($t[3529] = 2.9$, $p < .01$), but for the initial word, the effect was restricted to contexts where the following tone was /45/ ($t[3355] = 3.0$, $p < .01$) and /4/ ($t[3355] = 5.0$, $p < .01$).

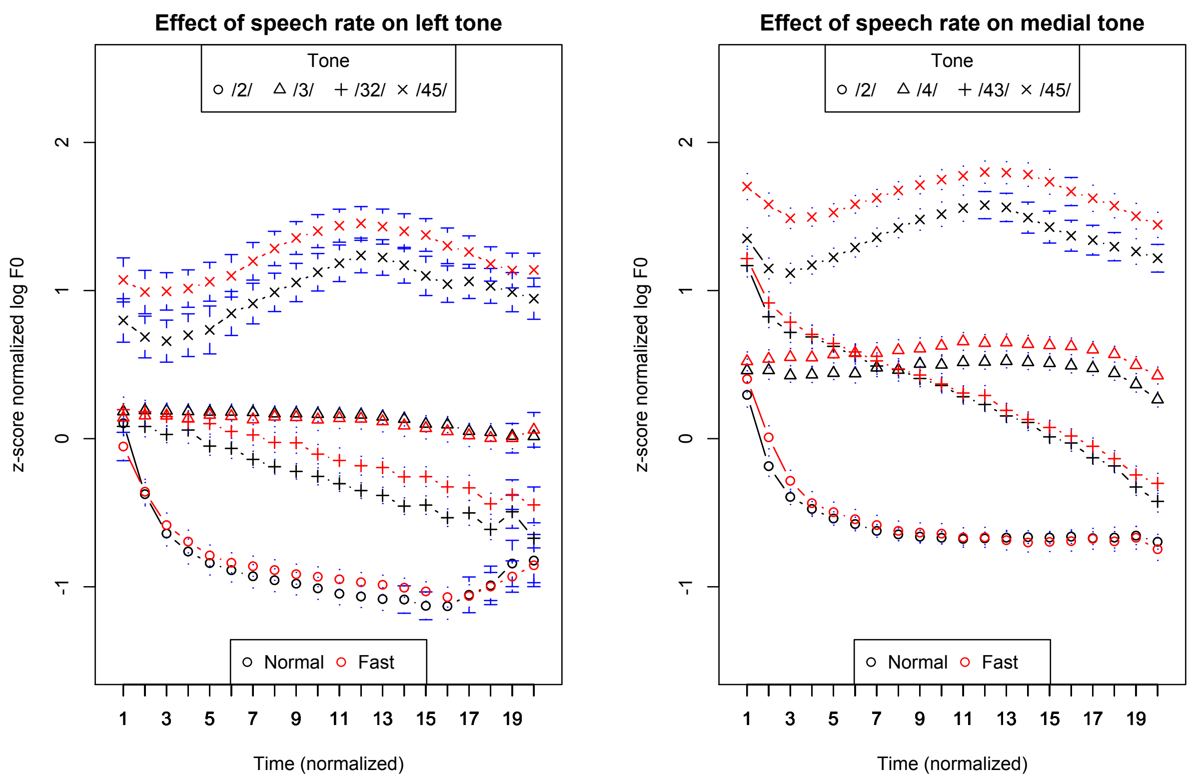


**Figure 10:** $F_0$ range expansion with fast speech rate.

In the initial word, a significant main effect of speech rate was also found for tone /2/ ($t[3465] = 7.5$, $p < .001$), tone /3/ ($t[2660] = -2.2$, $p < .05$), and tone /32/ ($t[3283] = -7.5$, $p < .001$). In the medial word, a significant main effect of speech rate was also found for tone /2/ ($t[3408] = -4.2$, $p < .001$) and tone /4/ ($t[3464] = -3.7$, $p < .001$). There was no general effect of speech rate on tone production for tone /43/, but a significant interaction was found for when this tone occurred in the context of adjacent tones /3.45/ ($t[3452] = 5.7$, $p < .001$). For each of these effects, tones produced during the faster speech rate were raised. It is notable that this $F_0$ raising is not restricted to the medial, monosyllabic word, but occurs across words in the stimulus sentences. Thus, one can reject the possibility that the medial word, which varies in tone relative to the adjacent targets, receives some type of prosodic prominence.

Yet, the production of tone on medial and initial words is not identical. While we have not statistically compared the production of identical tones across these words, a few patterns in Figure 10 are worthy of notice. First, tone /45/ is raised in medial monosyllabic words relative to its production in the final syllable of the initial word. Second, tone /2/ is raised in a similar fashion. These observations are discussed at greater length in §4.

*3.3 Durational differences by tone*

Figure 11 shows differences in the duration of each of the examined tones across each word. A mixed effects model was constructed for each word position with duration (in milliseconds) as the dependent variable, the initial/final tone identity as an independent variable, the medial tone identity as an independent variable, and speech rate as an independent variable. Speaker was treated as a random effect.

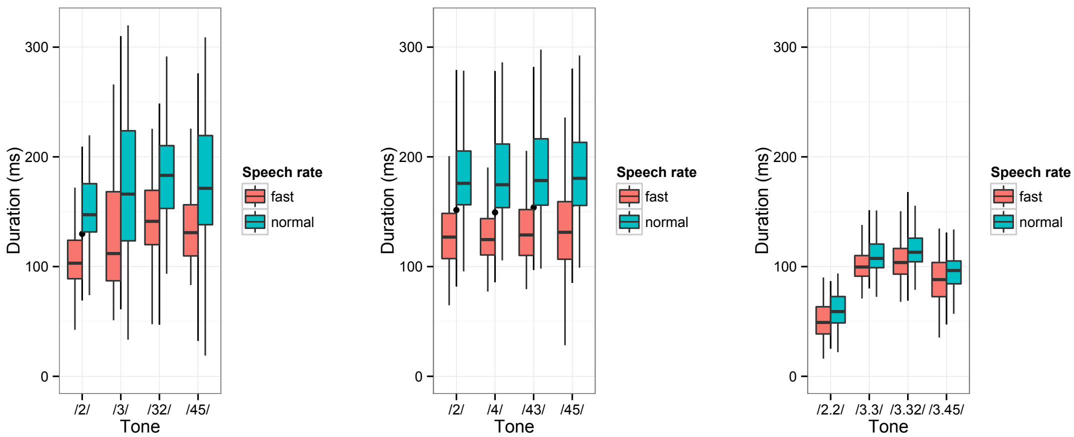


**Figure 11:** Duration differences by tone across words.

Tones varied in duration on the initial word. Tone /3/ was relatively short(t[1244] = -2.9, p < .01), whiles tones /32/ and /45/ were relatively long (t[1244] = 2.0, p < .05; t[1244] = 4.3, p < .001). In general, contour tones were longer than level tones in this word. In the medial position, there was no main effect of tone on duration. Tones in this word each had relatively similar durations. In the initial syllable of the final word, duration varied more substantially, but only between tone /2/ and the remainder, which were all tone /3/. Tone /2/ was significantly shorter than each of the other tones (t[1255] = -8.6, p < .001). On the whole, durational differences among tones were small within each word. However, unstressed syllables in the final word were substantially shorter than the stressed syllables analyzed on the initial and medial words, a finding in agreement with previous work on IT stress (DiCanio, 2008, 2010).

# 4 Discussion

*4.1 Tonal coarticulation*

On the whole, significant coarticulatory effects of adjacent tones were found in the IT data, but the strength of these effects depended heavily on whether the adjacent word contained a contour or level tone. Stronger effects were found when a tone was adjacent to a contour tone than when the same tone/word was adjacent to a level tone. One explanation for this finding is that contour tones exert stronger temporal demands on adjacent $F_0$ targets than level tones do. Since there are multiple rising and falling tones in the language, contours in IT necessarily contain multiple phonetic features (height, slope, $F_0$ termination, spectral tilt). Research modeling the production of level tones finds that they may be specified with only an $F_0$ height target but that contours require additional parameters (Xu and Prom-on, 2014). The prediction of this finding is that one anticipates greater tone sandhi to develop in phonological contexts involving contour tones than in those involving level tones.

Most of the observed effects with the IT data were assimilatory in nature. Assimilation was observed both in anticipatory contexts on the initial word, perseveratory contexts on the final word, and on the medial word (where the targets were modified on both sides). When tonal dissimilation occurred, it was restricted to anticipatory contexts and involved tone /45/. Tone /45/ was raised on the initial word when the following word contained tone /2/. In the medial word, tone /45/ was raised when the adjacent syllables contained tone /2/ and tone /2/ was lowered when the adjacent syllables contained tone /45/. The restriction of tonal dissimilation to anticipatory contexts matches findings on tonal coarticulation in Mandarin (Xu, 1998), Taiwanese (Peng, 1997), Tianjin Chinese (Zhang and Liu, 2011), and Malaysian Hokkien (Chang and Hsieh, 2012). For instance, high falling tones in Tianjin Chinese are raised before tones with a lowered $F_0$ onset on the following syllable. However, not all anticipatory tonal effects in IT were dissimilatory, suggesting that the relationship between position and the direction of tonal coarticulation only works in one direction, i.e. if dissimilation occurs, it occurs in an anticipatory context (but not vice-versa). Moreover, Zhang and Liu (2011) argue that tonal dissimilation is more common in right-dominant systems where the final tone in a sandhi group tends to be maintained. As IT has stem-final stress, the data here lend support to this view.

### *4.2 Speech rate and contrast preservation*

It is notable that the dissimilatory tonal coarticulation is restricted to contexts involving the highest and lowest tones in the IT data.[4] This is precisely the context where one would expect the *greatest* possible degree of assimilatory tonal coarticulation to occur, yet we observe dissimilation instead. Why might this be? The effects of speech rate on tonal coarticulation provide some additional insights into this finding. Across all speakers, the $F_0$ range was expanded with faster speech rate. This finding contradicts research showing that faster speech rate results in the loss of tonal contrast in lexical tone languages (Gandour et al., 1999; Xu and Sun, 2002) and a more general reduction in the pitch range (Bradlow, Kraus, and Hayes, 2003; Smiljanić and Bradlow, 2005). Moreover, despite the significance of the coarticulatory patterns in the IT data, most of the observed patterns are non-neutralizing. That is, the different contexts where the tones occur do not seem to trigger as large of an effect on tone production as one observes either in Mandarin (Xu, 1994) or Thai (Gandour et al., 1999). Despite increases in speech rate and the contexts where one might anticipate excessive assimilation, like in sentences with a /2/+/45/+/2/ sequence, tones are remarkably stable in IT.

One possible motivation for tonal preservation in IT lies in the functional load of tone in the language. Tone has a much higher functional load in Itunyoso Triqui than in many of the other languages where tonal coarticulation has been investigated. There are not only 9 lexical tones in Itunyoso Triqui, but tone is used to mark verb aspect, e.g. /ki$^{3}$ni$^{3}$ʔih$^{45}$/ 'I knew (PERF)' vs. /ki$^{2}$ni$^{3}$ʔih$^{45}$/ 'I will know (POT)', and person, /tʃa$^{43}$=ũh$^{3}$/ 'she eats' vs. /tʃa$^{43}$=ũh$^{4}$/ 'we (excl) eat'; /tʃah$^{4}$/ 'I eat' vs. /tʃa$^{43}$/ 'one eats.' As a comparison, Mandarin Chinese contrasts only four lexical tones and Thai, only five. Both of these languages lack inflectional morphology involving tone. Since tone plays such an integral role in IT, mechanical processes which result in tonal neutralization would be more deleterious to tone perception as they would be in languages where tone has a lower functional load. One potential way to preserve tonal contrasts in a system like IT would be to expand the speaker's overall pitch range when increases in speech rate or adjacent contexts make tonal assimilation more likely. As faster speech rate causes syllable shortening, expanding the space may permit easier perception of tonal contrast when tones are realized over shorter time spans.

There is some support for this view from cross-linguistic research on vowel-vowel coarticulation. Languages with fewer phonemic vowel distinctions, like Ndebele and Shona, show stronger coarticulatory effects between vowels than languages with a greater number of phonemic vowel distinctions, like Sotho (Manuel, 1990, 1999). The explanation here is that more coarticulatory variation is permitted in five-vowel systems than in seven-vowel systems since excessive variation in the latter is more likely to lead to over-

[4] Tone /1/ is lower than tone /2/, but it was not considered in the current study.

lap with other contrasts in the vowel space. Thus, languages constrain the degree of permitted variability ("output constraints" in Manuel (1990)) if it is likely to be deleterious for listeners to perceive phonological contrasts in a language.

One way in which this theory fits the IT data is in relation to tonal cues. There are four level tones and several contours that differ acoustically and perceptually mainly in $F_0$ height (DiCanio, 2012b). Thus, any significant assimilatory coarticulation in IT would have the potential to lead to tonal ambiguity. Note that tones /2/ and /1/ are already perceptually very similar and, apart from being lexically-contrastive, tones /2/ and /3/ also distinguish aspect on verbs. Falling tones /32/ and /43/ have virtually identical slopes and differ mainly in $F_0$ height (DiCanio, 2008). Unlike Mandarin Chinese and Thai, where many tones differ in slope as well as height, any shift in $F_0$ height has the potential to shift a tonal category in IT. This finding predicts tonal coarticulation to be more temporally constrained in languages which rely more on $F_0$ height as a cue than in those where slope is a stronger cue. However, this specific hypothesis remains to be tested with a larger sample of languages.

### *4.3 Alternate analyses*

Tonal hyperarticulation has been previously observed in work examining the production of tones in noise in Cantonese (Zhao and Jurafsky, 2009) and when tones occur in positions of prosodic focus (Scholz, 2012; Xu, 1999). In each of these cases, a trigger (language-external or internal) prompted speakers to hyperarticulate tones. This previous work might lead one to hypothesize that the hyperarticulated tones in IT are the result of prosodic focus. Yet, there are reasons to doubt this view. First, focus in IT is obligatorily specified by position in IT. The default word order is Verb + Subj + Obj, but responses to WH-questions obligatorily require a fronted noun phrase. Thus the response to the question /ũ$^{3}$-sĩ$^{3}$ tʃa$^{43}$ ru$^{4}$ne$^{43}$/ 'Who ate the avocado?' is /ku$^{3}$ri$^{4}$sjã$^{43}$ tʃa$^{43}$ ru$^{4}$ne$^{43}$/, (Christian eat.PERF avocado) 'Christian ate the avocado.', not the default order /tʃa$^{43}$ ku$^{3}$ri$^{4}$sjã$^{43}$ ru$^{4}$ne$^{43}$/, (eat.PERF Christian avocado). An in-situ noun phrase is ungrammatical as a response. The same fronted order occurs with nouns which express new information. In the IT data examined here, the fronted order never occurs. Second, one observes $F_0$ range expansion not just in the medial noun in the examined sentences, but also in the final syllable of the initial verb (see Figure 10). Thus, hyperarticulation is not restricted to specific positions in the produced utterances, but rather to the entire utterance in fast speech. The hyperarticulated tones in the IT data are not prosodically-prominent.

Another possible analysis for the fast speech data is that speakers do not just increase speech rate, but their emotional state in the recording condition. The idea here is that one might observe more tonal hyperarticulation during "excited" speech than in the slower speech rate. There is some evidence that excitement may result in hyperarticulated tonal targets (Luksaneeyanawin, 1998) and output constraints in speech production may vary according to speech style (Manuel, 1990). Though IT speakers were only instructed to increase their speech rate, it is also particularly difficult to distinguish between a more excited speech register and one which reflects just a faster speech rate in a field setting. The novelty of being recorded for IT speakers may also have contributed to them speaking with a clearer register than usual. $F_0$ range expansion is a characteristic of clear speech (Smiljanić and Bradlow, 2005).

Yet, both of these possibilities beg the question "Why expand tonal distinctions at the expense of other phonetic features?". Glottal stops undergo reduction to creaky phonation in running speech in IT (DiCanio, 2008, 2012a) and singleton affricates spirantize when speech rate increases (DiCanio, 2012c). If these other phonological contrasts (phonation type, the affricate-fricative contrast) undergo significant reduction, why does tone do the opposite? The only possible explanation must be that speakers actively enhance and preserve phonological tone contrasts. Such active enhancement has been shown to target specific phonological distinctions over others (Keyser and Stevens, 2006).

## 5 Conclusions & Future Work

There was a significant influence of tonal context and speech rate on the production of IT tones. Contour tones triggered stronger coarticulatory influence on adjacent tonal targets than level tones did. Yet, despite the observed tonal variation, tonal distinctions were largely maintained and very little overlap in tonal trajectories occurred. Contra previous work (Gandour et al., 1999; Xu, 1994), faster speech rate resulted in an expansion of the $F_0$ range for all speakers. The increased $F_0$ range and processes of tonal dissimilation between the highest and lowest tones in the language result in the preservation of tonal contrasts in IT.

The current work has several important ramifications to work on tone production and perception. First, the weighting of tonal cues within a particular language may influence the degree of coarticulatory variation. Tonal systems which rely more heavily on $F_0$ height may undergo less contextually-induced coarticulation than those systems which rely more heavily on $F_0$ slope and direction. Apart from IT, many Oto-Manguean languages contrast at least three tone heights in level tones and/or contour tones (Anderson, Martínez, and Pace, 1990; Beal, 2011; DiCanio, Amith, and Castillo García, 2014; Cruz, 2011; Jamieson, 1977; Pike, 1948; Castillo Martínez, 2011). Thus, tonal contrast preservation may be a characteristic of many languages within the family. This pattern may even underlie differences in the degree of tonal coarticulation among East and Southeast Asian languages which differ in terms of their inventories of level tones, e.g. Mandarin vs. Cantonese. This prediction should be specifically tested across different languages. Second, relatively few theories of speech production involve a mechanism that can account for tonal dissimilation. Such a process may unfold via an inhibitory mechanism in speech production planning (Tilsen, 2013). Modelling of the coarticulatory processes here is currently underway using the PENTAtrainer 2 model (Xu and Prom-on, 2014), though an inhibitory mechanism in speech planning for tone has not yet been incorporated. The IT data here suggest that such a mechanism may be necessary.

The novel findings in the current work highlight how research on endangered and minority Meso-American languages contribute to general issues within the literature on tonal phonetics and phonology. The construction of language-independent and general theories of tone production and perception is only possible if the languages that one examines come from a variety of families and geographic locations. As we consider a larger typology of languages and tonal systems, it is not only our knowledge of phonetic possibilities that is enhanced, but also our ability to discern broader generalizations regarding speech production.

# 6 Appendix

**Table 3:** Tonal coarticulation stimuli.

| Tonal combinations | | | Sentence | Gloss |
|---|---|---|---|---|
| Initial | Medial | Final | | |
| 3.45 | 45 | 3.45 | a$^{3}$tʃĩh$^{45}$ sĩh$^{45}$ tʃa$^{3}$kah$^{45}$ | '*The man asks for a pig.*' |
| 3.32 | 45 | 3.32 | ri$^{3}$jũ$^{32}$ sĩh$^{45}$ re$^{3}$to$^{32}$ | '*The man measures the blanket.*' |
| 3.3 | 45 | 3.3 | ni$^{3}$ʔi$^{3}$ sĩh$^{45}$ ja$^{3}$kʷeh$^{3}$ | '*The man knows Oaxaca City.*' |
| 2.2 | 45 | 2.2 | na$^{2}$ka$^{2}$ sĩh$^{45}$ si$^{2}$ʔnih$^{2}$ ʈ̺ʂoʔ$^{3}$ | '*The man is picking up a pillow.*' |
| 3.45 | 45 | 3.45 | na$^{3}$no$^{3}$ʔoh$^{45}$ jo$^{4}$ si$^{3}$kih$^{45}$ | '*I am looking for the basket of copal.*' |
| 3.32 | 4 | 3.32 | ri$^{3}$jũ$^{32}$ jo$^{4}$ ru$^{3}$ne$^{32}$ | '*He is measuring the basket of beans.*' |
| 3.3 | 4 | 3.3 | ka$^{3}$ju$^{3}$ jo$^{4}$ ne$^{3}$tã$^{3}$ | '*The basket of string beans fell.*' |
| 2.2 | 4 | 2.2 | ka$^{2}$tʃĩ$^{2}$ jo$^{4}$ tʃi$^{2}$ʔŋgah$^{2}$ tsi$^{32}$ | '*I am asking for a basket of corn smut.*' |
| 3.45 | 45 | 3.45 | a$^{3}$tʃĩh$^{45}$ tʃe$^{32}$ tʃa$^{3}$kah$^{45}$ | '*My father asks for a pig.*' |
| 3.32 | 32 | 3.32 | ri$^{3}$jũ$^{32}$ tʃe$^{32}$ re$^{3}$to$^{32}$ | '*The man is measuring the blanket.*' |
| 3.3 | 32 | 3.3 | ni$^{3}$ʔi$^{3}$ tʃe$^{32}$ ja$^{3}$kʷeh$^{3}$ | '*The man knows Oaxaca City.*' |
| 2.2 | 32 | 2.2 | na$^{2}$ka$^{2}$ tʃe$^{32}$ si$^{2}$ʔnih$^{2}$ ʈ̺ʂoʔ$^{3}$ | '*The man is picking up a pillow.*' |
| 3.45 | 45 | 3.45 | na$^{3}$no$^{3}$ʔoh$^{45}$ ko$^{2}$ tʃa$^{3}$kah$^{45}$ | '*I am looking for twenty pigs.*' |
| 3.32 | 2 | 3.32 | ri$^{3}$jũ$^{32}$ ko$^{2}$ re$^{3}$to$^{32}$ | '*He is measuring twenty blankets.*' |
| 3.3 | 2 | 3.3 | ka$^{3}$ju$^{3}$ ko$^{2}$ ne$^{3}$tã$^{3}$ | '*Twenty string beans fell.*' |
| 2.2 | 2 | 2.2 | ka$^{2}$tʃĩ$^{2}$ ko$^{2}$ si$^{2}$ʔnih$^{2}$ ʈ̺ʂoʔ$^{3}$ | '*I am asking for twenty pillows.*' |

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