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The Phonology and Phonetics of Consonant-Tone Interaction

A dissertation submitted in partial satisfaction of the

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in Linguistics

by

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To Paul

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ABSTRACT OF THE DISSERTATION

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While it has long been known that consonants and tones interact with one another, the question of how they interact has received relatively little attention in the literature. I approach this question first from the perspective of a cross-linguistic survey of consonant-tone interaction. The results show that, while the more commonly studied interaction between voicing and low tone is the most frequent type of consonant-tone interaction, consonant-tone interaction also includes a much larger variety of consonants than is often assumed (e.g. Bradshaw, 1999; Bao, 1999; Odden, 2002; Yip, 1995). It also includes a wider variety of tone types than have been assumed by earlier phonological models.

This survey, along with the phonetic connection between the realization of laryngeal features and the production of F0, becomes the basis for the theoretical

approach taken in the dissertation. I discuss the concept of a tone span and argue that this provides an environment in which a suprasegmental feature and a segmental feature can interact without being merged into a single feature; because many consonants are able to interact with tone, I argue that a merged feature approach cannot account for the full range of data. Within a tone span, phonetically based constraints require compatible laryngeal features to co-occur or prohibit incompatible from co-occurring. I further explore these ideas by providing a detailed account of the phonology of two typologically distinct languages, Bade and Kam.

Finally, I examine the F0 patterns in Bade to see how the phonology is reflected in the phonetics. The results show that voiced obstruents, with a low tone affinity, lower F0, and voiceless obstruents, with a high tone affinity, raise F0. Sonorants have an intermediate effect on F0 and are neutral with regard to consonant-tone interaction. Implosives are also neutral with regard to consonant-tone interaction, but they show similarities to both voiced and voiceless consonants in their effect on F0. The tone span, marked with the phonological boundaries hypothesized for Bade, is also shown to be a phonetically distinct unit for F0 measurement.

Chapter 1 Introduction of Research Question

The autosegmental properties of tone have received considerable attention in the phonological literature, providing many new avenues for linguistic research. Perhaps it is for this reason that the interactions between tone and segments have received considerably less attention. Nevertheless, in a wide variety of languages, tone does interact with segmental properties. Most often, and most frequently addressed in the literature, tone interacts with voicing, but it also affects and is affected by other laryngeal features.

The primary goal of this thesis, then, is to explore how and why consonants and tones interact with each other. Beginning with a survey of languages in which consonants interact with tone, I describe the ways in which consonants and tones interact with one another in different languages. I then discuss the phonetic motivation for these interactions and propose a theory that is wide-ranging enough to account for these data. Finally, I provide phonetic data that provides further insights into the mechanisms of consonant-tone interaction in one language.

To the extent that the phonetics are reflected in the phonology, it is unsurprising that consonants and tones interact with one another. It has long been known that obstruents affect the fundamental frequency at the onset of the following vowel (Hombert, 1978; House & Fairbanks, 1953). This follows from the fact that fundamental frequency and properties such as voicing, aspiration, and glottalization are all controlled by the muscles and the physiology of the larynx. Moreover, at least in some languages, these effects are exaggerated beyond what is physiologically necessary and act as a cue for distinguishing between types of consonants (Honda, 2004). Historically, these phonetic differences are the recognized cause of tonogenesis in numerous languages (Haudricourt, 1972; Matisoff, 1973).

However, in a phonology that relies on mental representations of shared properties between sounds, the interaction between consonants and tones becomes more difficult to account for. In a straightforward phonological interaction, two phonemes are thought to interact by virtue of shared features; for example, a voiceless obstruent assimilates to a following voiced obstruent through the addition of the feature [voice], or a nasal obstruent assimilates to the place of the following stop through the acquisition of its place feature. However, the cross-linguistic data show that nearly any laryngeal feature can interact with tone. Consequently, I argue that consonant-tone interaction cannot be directly accounted for via shared features between consonants and tones. Instead, following Peng (1992), I account for this behavior in a framework of phonetically motivated constraints that prevent independent features from co-occurring.

1.1 Introduction of data

To make these ideas more concrete, in this section I provide some data covering the range of issues this thesis addresses. Nupe (Niger-Congo, Nigeria) is a typical example of consonant-tone interactions. According to Hyman (1970), a high tone becomes rising following a low tone, provided that the high tone occurs in a syllable with a phonetically voiced onset. In autosegmental terms, low tone spreads to the right unless a voiceless obstruent intervenes. Data are provided in (1):

1. Tone lowering in Nupe (Hyman, 1970)
   a. /èdé/ > [èdě] ‘clothes’
   b. /kùlé/ > [kùlě] ‘bell’
   c. /ǹdá/ > [ǹdǎ] ‘father’
   d. /yèkó/ > [yèkó] ‘road’ (*yèkǒ)

This effect of the obstruent on the spreading has been viewed variously as a conditioning effect, where voiced consonants trigger low tone spreading (Bradshaw, 1999; Hyman, 1970), or a blocking effect, where voiceless obstruents block low tone spreading (Peng, 1992).

It has been argued that [voice] is the only feature that is able to interact with tone (e.g. Bradshaw, 1999), and that it interacts specifically with low tone. Bradshaw (1999) accounts for this by means of a single privative feature representing both low tone and voicing. For languages like Nupe, this hypothesis seems tenable. However, data from a variety of languages show that this claim is too strong.

For example, in Bade (Chadic, Nigeria), non-implosive voiced obstruents block high tone spreading, as shown in (2).

2. High tone spreading in Bade (Schuh, 2002)
   a. /nə́ tə̀nkə̀kú/ > nə́ tə́nkə́kú ‘I pressed’
   b. /nə́ ɗùwàɬú/ > nə́ ɗúwáɬú ‘I got tired’
   c. /nə́ tə̀mbə̀lú/ > nə́ tə́m**b**ə̀lú ‘I pushed’ (*tə́mb**ə́**lú)
   d. /nə́ bàzàrtú/ > nə́ **b**àzàrtú ‘I shamed’ (*b**á**z**á**rtú)

While this could easily be accounted for in a [voice]-only system, Bade also requires that voiceless obstruents block low tone spreading. Data are provided in (3).

3. Low tone spreading in Bade (Schuh, 2002)
   a. /dʒə̀.ɗgə́ kó:rón/ > dʒə̀.ɗgə̀ kó:rón 'we followed a donkey'
   b. /dʒə̀ kə̀rə́ kó:rón/ > dʒə̀ kə̀rə̀ kó:rón 'we stole a donkey'
   c. /dʒə̀ də̀psə́ kó:rón/ > dʒə̀ də̀**ps**ə́ kó:rón ‘we hid a donkey’
   d. /dʒə̀ gàfá kó:rón/ > dʒə̀ gà**f**á kó:rón ‘we caught a donkey’

The most straightforward analysis of this data is that voiceless obstruents are indeed interacting with tone, counter to Bradshaw’s claim; a more detailed argument that this is the case will be provided in section 3.3.

Consonant-tone interaction also occurs in languages where [voice] does not participate in the phonology. For example, Kam (Dai-Kadai, China), addressed in section 3.4, lacks voiced obstruents, but both aspiration and glottalization interact with tone, a result that is clearly not predicted in a system where only [voice] interacts with tone. Although there are not any known phonological alternations in Kam that demonstrate this interaction, there are clear phonotactic patterns showing that rising tones occur after all aspirated onsets, but never after voiceless unaspirated onsets (as in 4), and high register tones (including [33]) cannot occur on long vowels preceding glottalized codas (as in 5). Sonorants are neutral with regard to these restrictions.

4. Aspiration and tone in Kam (Long & Zheng, 1988)[1]
   a. paː⁵⁵ 'fish' *but* *pʰaː⁵⁵
   b. pʰaː³⁵ 'grey' *but* *paː³⁵

5. Glottalization and tone in Kam
   a. soːtˀ ³¹ 'vanish' *but* *soːtˀ ⁵³
   b. mətˀ ¹¹ 'ant' *but* *mətˀ ³³

The Kam data also show that languages vary not only with regard to the type of consonant that is able to interact with tone, but also with regard to the type of tone with which consonants can interact. Even in languages where tone is assigned to each syllabe, tone may be divided into contour and register, as it is for the Kam examples in (4) and (5). I use register here to refer to the division of the overall tone space into high (3-5 in Chao numbers) and low (1-3). These spaces may be further divided into contour tones high (5, 3) and low (3, 1). This is represented schematically in Figure 1.

```
5 ------------------------------------ high contour (h)
4      High register (H)
3 ------------------------------------ low contour (l) / high contour (h)
2      Low register (L)
1 ------------------------------------ low contour (l)
```

Figure 1. Schematic division of the tone space into registers

[1] Transcriptions for Kam use Chao's (1933) tone letter system, in which 1 is low and 5 is high.

The register and contour specifications for the previous Kam examples are given in (6), with capital letters used to represent register and lower-case letters for contour.

6. Kam examples with contour and register specification
   a. paː^{55} [H,h] *but* *pʰaː^{55} [H,h]
   b. pʰaː^{35} [H,lh] *but* *paː^{35} [H,lh]
   c. soːtˀ ^{31} [L,hl] *but* *soːtˀ ^{53} [H,hl]
   d. mətˀ ^{11} [L,l] *but* *mətˀ ^{33} [H,h]

The register tone typically applies to the entire syllable, while the contour tones may vary over the course of the syllable. Thus, it is often assumed that there is an inherent hierarchical relationship between register and contour, although there is some debate regarding this (see, e.g., Bao, 1999; Yip, 1995). The term *register* is also used in the literature to describe voice quality distinctions, often ones that have a specific tonal quality associated with it, but I do not address such systems here.

Not only do contour and register tones interact with consonants, but pitch accent and intonation have also been claimed to interact with consonant features. For example, the Maasbracht dialect of Limburgian (Hermans & van Oostendorp, 2000) has two pitch accents, which contrast on bimoraic stressed syllables. In non-final position, these are realized as falling and high tones.[2] These tones are fully contrastive. However, falling tone is not permitted in a syllable that is closed with a sonorant which in turn precedes a voiceless obstruent. Data are provided below:

7. Contrastive pitch accent in Limburgian (Hermans & van Oostendorp, 2000)
   a. ǽ̀rɣər ‘worse’ ǽrɣer ‘to annoy’
   b. éèdər ‘every’ ééder ‘earlier’
   c. páàtər ‘father’ wáátər ‘water’

[2] The high tone is referred to as *dragging* and is realized as a falling-rising tone in final position.

8. Falling tone blocked in Limburgian

a. bálkan	'the Balkans'	*bâlkan
b. hǽlp	'to help'	* hæ̂lp
c. rǽntə	'shop'	* ræ̂ntə
d. láŋk	'long'	* lâŋk

In the Seoul dialect of Korean (Jun, 1996)[3], consonant-tone interaction clearly belongs to post-lexical phonology; here, consonants interact with intonation rather than with lexically specified tone. There are two possible tonal patterns for non-IP-final Accentual Phrases in Seoul Korean: LHLH and HHLH. The HHLH pattern only occurs following AP-initial aspirated and tensed consonants, while the LHLH pattern follows sonorants and lax obstruents. Jun suggests that this effect is among the phrase-initial strengthening phenomena in Korean.

The above data are indicative of the types of data addressed by this thesis. Consonants are also able to interact with tone in less direct ways, for example, as they contribute to the shape of the syllable (see Jie Zhang, 2002), but I limit my work here to interactions that are dependent on specific laryngeal properties of the consonants in question.

1.2 Literature review

Although the literature on this topic is not extensive, various theories have been put forward to account for consonant-tone interaction. For the sake of convenience, I divide these into two categories, feature-based and constraint-based, since the constraint-based approaches included here tend not to rely on specific feature theories for an explanation. The feature-based theories, on the other hand, account for

[3]Jun shows similar facts for the Chonnam dialect.

consonant-tone interaction by assigning the same features to those consonants and tones that interact with one another.

1.2.1 Feature-based theories

Those who place the theoretical basis for consonant-tone interaction within the features themselves typically assign some type of laryngeal feature to tone, since the fundamental frequency of a vowel and the laryngeal properties of a consonant are both regulated through movements of the larynx and vocal folds. Halle and Stevens (1971) are the first to include tone features within a more general system of laryngeal features. They associate the feature [+stiff vocal folds] with voiceless consonants and high tone, while [+slack vocal folds] is associated with voiced consonants and low tone. In addition, they include the features [spread glottis] and [constricted glottis] as laryngeal features with no tonal reflex. The resulting feature specifications for various consonants are summarized in the following table; presumably plain nasals are in the same category as the plain approximants [w j].

	b, low tone	p, high tone	p^h, h, w̥[4]	$p^ʔ$, ʔ	w, mid tone
spread glottis	-	-	+	-	-
constricted glottis	-	-	-	+	-
stiff vocal cords	-	+	+	+	-
slack vocal cords	+	-	-	-	-

Table 1. Laryngeal feature specifications for consonants and tone (Halle and Stevens 1971)

This system, then, predicts that the stiffness of the vocal folds will interact with tone, but the glottal features [spread] and [constricted] will not do so. Various later researchers have criticized this system for permitting impossible combinations of

[4] Voiceless nasals and laterals also belong in this category; they are [+ spread, -voice] in the feature system used by Clements (1985:234).

features and for over-predicting. In turn, they have proposed less complex systems of laryngeal features.

The simplest, and strongest, of these proposals is that of Bradshaw (1999). She proposes that we can consonant-tone interaction by a single privative feature, L/[voice], which can attach to various nodes in the syllable structure. The place of attachment determines whether it will result in low tone or voicing. Thus, Bradshaw predicts that only those sounds that are phonologically voiced can interact with tone.

Yip (1995) offers a more complex featural proposal. Using feature geometry, she divides the laryngeal node into register and glottal aperture. In this system, register tone and voicing are grouped together as register, and this feature dominates tone contour, represented by the pitch nodes; the repetition of the pitch node indicates a temporal sequence, providing two slots so that contour can change over the course of the syllable.

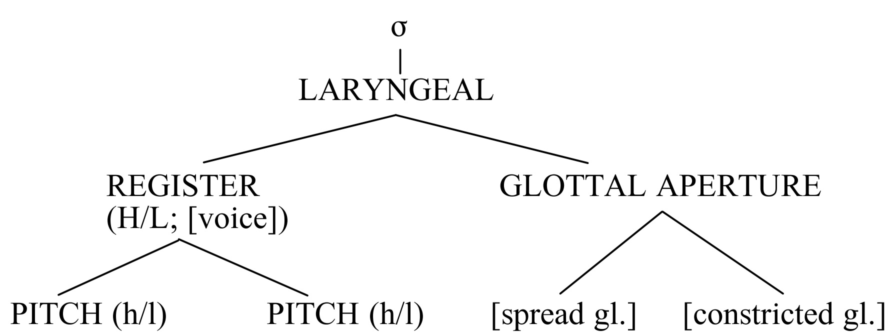


Figure 2.   Incorporation of tone into the laryngeal node (Yip 1995)

This model predicts that only register tone, not contour tone, should interact with voicing, since both register and voicing occupy the same slot in the feature geometry. Moreover, it predicts that other laryngeal features, [constricted glottis] and [spread glottis], should be unable to interact with tone.

Bao (1990) provides a slightly different geometry for the laryngeal node, shown below:

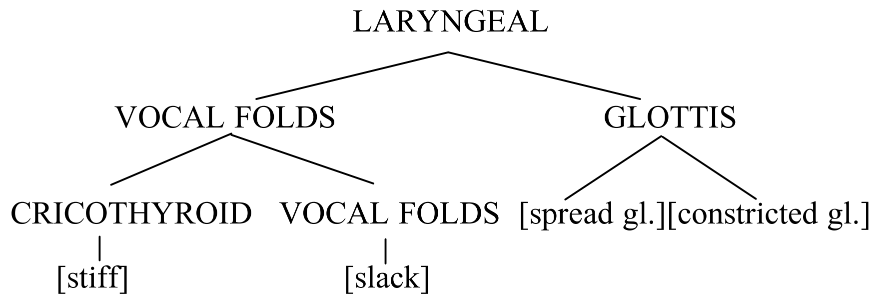


Figure 3. Incorporation of tone into the laryngeal node (Bao 1990)

In Bao's model, two features, [stiff] and [slack] define voicing and tone. The feature [stiff] corresponds to voiceless obstruents and high tone, both contour and register, while [slack] corresponds to voiced obstruents and low tone. This, then, is an adaptation of the feature system proposed by Halle and Stevens (1971). This feature system differs from Yip's in that it does not limit consonant-tone interactions to tonal register, and it predicts that consonants with the features [stiff/slack] should interact with tone. However, like Yip's, it maintains the prediction that the glottal features [constricted glottis] and [spread glottis] and tone should not interact with one another.

1.2.2 Constraint-based theories

In contrast to this feature-based line of research, a second line of research uses a constraint-based approach to account for consonant-tone interaction. Peng (1992) is a pre-Optimality Theory account couched in Grounded Phonology (Archangeli & Pulleyblank, 1994). More recently, OT accounts have been proposed for the Maasbracht dialect of Dutch (Hermans & van Oostendorp, 2000), Thai (Morén & Zsiga, 2006), and Yabem (Hansson, 2004b). Each of these uses implicational constraints, or equivalently, grounding constraints, in order to effect a relationship between consonant features and tone features. For example, Hansson (2004b) proposes the following constraint to account for tone-induced voicing in Yabem:

9. L $\supset$ $[\text{voi}]_\sigma$: For each syllable, if it carries low tone, then every segment within that syllable must be [+voice].

Hermans and van Oostendorp advocate a similar constraint for Limburgian, where voiceless obstruents require a preceding tone to be high. The same constraint that relates voicing to low tone in Yabem is able to relate voicelessness to high tone in Limburgian because L$\supset$$[\text{voi}]_\sigma$ is satisfied vacuously by any non-low tone.

In the case of Thai, it is not voicing but glottalization that interacts with tone, requiring a low tone to precede a glottalized coda. Morèn and Zsiga propose the constraint C.G.CODA→L to account for this effect:

10. **C.G.CODA→L**: Constricted glottis coda segments must be associated with low tone.

Each of these authors argues that the proposed constraint is phonetically grounded; [voice] and L are connected by virtue of the lowering effect voicing has on F0, while [constricted glottis] is linked to L because creakiness lowers F0. The underlying assumption is that constraints link two categories of features by motivating a connection between them phonetically. However, each of these researchers is addressing a single phenomenon in a single language and, consequently, they do not attempt to generalize their claims into a theory of consonant-tone interaction.

The most through treatment of consonant-tone interaction in a constraint-based system predates OT. Peng's (1992) work is the first to systematically address consonant-tone interaction under the assumption that tone and voice share neither features nor autosegmental representations. Peng writes in the framework of Grounded Phonology, a rule-based phonological theory in which the possible rules are limited according to certain parameters. In this theory, F-elements [essentially, features] are combined into larger units via these rules; however, the possible combinations are further limited by Grounding Conditions, which determine whether the resulting representation is phonologically well-formed—these conditions, then, are equivalent to constraints.

Peng's approach to consonant-tone interaction relies on defining grounding conditions prohibiting combinations of F-elements for consonants and tones. These conditions must be grounded, i.e. phonetically motivated, and they are always in the form of implicational statements, either "If *a*, then *b*", or "If *a*, then not *b*." While tone and voice are represented on separate autosegmental tiers in this theory, individual features are considered formally linked by a path if a tone F-element and a voice F-element are both associated to the same mora, whether directly or indirectly. Thus, if a language makes use of a condition on consonant and tone features, then it will apply whenever there is a path between a consonantal F-element and a tonal F-element, thus preventing certain combinations from occurring.

Peng focuses on the relationship between voicing and tone. He considers three binary features, high (HI), low (LO), and voiced (vd). There are, then, 32 possible conditions on tone and voice; 16 are phonetically motivated, and 16 are not (p. 202-3), as listed below:

11. Phonetically motivated conditions
    a. If +HI, then –vd
    b. If +HI, then not +vd
    c. If –HI, then +vd
    d. If –HI, then not –vd
    e. If +LO, then +vd
    f. If +LO, then not –vd
    g. If –LO, then –vd
    h. If –LO, then not +vd
    i. If –vd, then +HI
    j. If –vd, then not –HI
    k. If –vd, then –LO
    l. If –vd, then not +LO
    m. If +vd, then –HI
    n. If –vd, then not +HI
    o. If +vd, then +LO
    p. If +vd, then not –LO

12. Phonetically unmotivated conditions
    a. If +HI, then +vd
    b. If +HI, then not -vd
    c. If –HI, then -vd
    d. If –HI, then not +vd
    e. If +LO, then -vd
    f. If +LO, then not +vd
    g. If –LO, then +vd
    h. If –LO, then not -vd
    i. If –vd, then -HI
    j. If –vd, then not +HI
    k. If –vd, then +LO
    l. If –vd, then not -LO
    m. If +vd, then +HI
    n. If –vd, then not -HI
    o. If +vd, then -LO
    p. If +vd, then not +LO

In addition, Peng proposes a grounded condition on the feature constricted glottis for Ngizim (p. 73): If –HI, then not +[constricted glottis]. The phonetically motivated conditions are predicted to be available to grammars, while the unmotivated conditions are predicted never to be used. Peng demonstrates how these conditions are applied in several languages; however, he does not conduct a survey to determine whether all and only the proposed conditions are necessary.

1.3 Research approach

While the study of consonant-tone interaction is certainly not new to the field of linguistics, as the literature review above suggests, it is not a well-studied topic. The survey in Chapter 2 shows that the phenomenon itself has been described for a wide variety of languages. However, perhaps because most of these languages are understudied, little of the existing work goes much beyond the descriptive level. Consequently, little has been done to compare the different theoretical approaches described in the previous section.

One goal of the current research is to compare different theoretical claims regarding consonant-tone interaction. The major difficulty with the major feature-based approaches reviewed in the previous section, as already mentioned, is that their predictions are too narrow: only specific types of laryngeal features can interact with tone in these systems. Moreover, for some of these theories, the proposed feature geometry predicts that consonants can only interact with a specific manifestation of tone, such as register tone or contour tone.

The survey in Chapter 2 shows that these predictions are too limited. Voiceless obstruents are able to interact with tone in languages such as Bade, and moreover, consonants such as implosives, fricatives, aspirated stops, and glottal or glottalized stops interact with tone as well. Furthermore, all types of tones are able to interact with consonants, from lexical register and contour tones to pitch accent and even post-lexical intonation. Because of this wide range of data, it seems that any account that is completely dependent on creating shared representations will ultimately fail. However, I do address the issue of laryngeal features more thoroughly in Chapter 3; in particular, in 3.3.8 I consider whether a privative voice feature is sufficient or whether a binary voice feature is necessary.

Among the other approaches, only Peng's addresses data from more than one language. If his proposed constraints are intended to be both universal and absolute (as Downing and Gick (2001) seem to assume), then his account is certainly problematic. For example, there should be no languages where a voiceless consonant can lower F0 since such a connection is ungrounded in Peng's system and violates a proposed constraint; yet voiceless aspirated consonants do lower tone in a variety of languages. Peng himself does not seem to make this assumption about his constraints, however. Rather, he states that, the stronger the phonetic motivation for any given condition, the more likely it is that a language will invoke this condition, and the more likely it is that this condition will be widely applied in the grammar—though this concept is not formalized. Thus, for Peng, a connection between low tone and voicing is presumably more prevalent than a connection between low tone and aspiration simply because the phonetic connection between low F0 and voicing is more salient or more stable cross-linguistically. Also, for Peng, constraints can be ordered with respect to rules, and so it is not necessary for a constraint to apply throughout the grammar even if it is active in a language.

While I generally follow Peng's theory, his work does not thoroughly address the question of which constraints are phonetically grounded. While voicing seems to interact fairly consistently with tone—voiced obstruents show an affinity for low tone and voiceless obstruents for high tone across languages, features such as [spread glottis] and [constricted glottis] show less consistent behavior. For example, aspiration shows an affinity for low tone in Kam (and more specifically, for rising tone), but in Korean, aspiration is connected with high intonation patterns. This is potentially troubling for a phonetically based account. There are at least two ways phonetic grounding could be maintained in light of such an apparent disparity. One approach, argued for the historical case of tonogenesis in Athabaskan languages (Kingston, 2005), is that the same glottal feature can result in either high or low tone, depending on the timing of the glottal gesture. If this is the case, then disparate constraints such as [sg]→H and [sg]→L might both be considered phonetically grounded. A second approach would advocate only one type of phonetic grounding and address instead the nature of the phonology involved. For example, it is possible that only a connection between [+spread glottis] and low tone is phonetically grounded, but in some languages the tone "assimilates" to the glottal feature while in others it "dissimilates" from it. In fact, implicational constraints are able to effect such seemingly contradictory results, as shown above for Dutch. In Section 3.5, I explore these approaches for various consonant types, comparing the predictions with the available phonetic and phonological data and conclude that, unless the laryngeal feature set is expanded beyond what evidence currently merits, contradictory constraints are in fact necessary.

This work also differs from Peng's in addressing the domain in which consonant-tone interaction takes place. For Peng, the connection between the two relies on a specific feature geometry. I instead use span theory, discussed in Section 3.1, to provide a common domain to consonants and tones.

Finally, in Chapter 4, I present results from Bade data regarding consonant-tone interaction. While the data come from a small corpus of utterances, there are nevertheless statistically significant results showing the effects of consonants on tones in Bade and suggesting that the tone span is a measurable domain in the language.

Chapter 2 A Survey of Consonant-Tone Interaction

In order to understand the phenomenon of consonant-tone interaction, the first task is to examine the scope of this interaction in different languages. While the survey presented in this chapter is not the first survey of this nature—that distinction, to my knowledge, belongs to Bradshaw (1999)—it is the first to include considerable amounts of data from non-African languages. Bradshaw comes to the conclusion that voicing is the only consonantal property that is able to interact with tone; this survey shows that although voice-tone interaction is the most common type of interaction, it is also by no means the only one.

In some sense, it is impossible to conduct a well-balanced survey of consonant-tone interaction since many languages are not tone languages, and of those that are, relatively few have documented interaction between consonants and tones. The survey presented here includes data from previous surveys of consonant-tone interaction, such as Bradshaw (1999) and Moreton (2006), as well as from Yip's overview of tone languages (Yip, 2002). Additional data was obtained through a search of journal articles and reference grammars of tone languages, with particular effort made to gather data from different language families and areas than previous surveys included. The resulting 61 languages and dialects represent 15 major language families from Africa, Asia, the Americas, Europe, and Oceania.

While it is not possible to completely balance the data in this survey, particular language families are, in some sense, over-represented in these data; in particular, many Wu dialects[5] and Mijikenda languages are included. However, their inclusion

[5] Chinese linguists tend to refer to all languages in the Chinese language family as dialects, most likely because they are spoken in China and share a single writing system. Wu is comparable, in this sense, to Mandarin or Cantonese in being a major regional dialect subgroup. However, even within the Wu dialects included in this paper, anecdotal evidence indicates that not all are mutually intelligible.

has value for several reasons. First, it demonstrates the strength of the interactions that are displayed consistently in these languages: if diverging dialects or languages continue to retain a feature that they presumably all inherited from the same source, it enhances the certainty that this feature is phonologically natural and learnable. Second, in the case of the Wu dialects, it reveals the differences that can occur even among closely related languages. While all the Wu dialects included in the survey connect voicing to low tone, and most relate voicelessness to high tone as well, other sounds show more variation. Among these dialects, nasals, glottal stops, /h/, aspiration, and glottalized nasals all interact with tone, but in no dialect is it documented that all of these sounds interact with tone. In fact, it is often specific phonological factors that distinguish one dialect from another. For example, the two Kammu dialects included in the survey are mutually intelligible, but their pattern of consonant-tone interaction is completely different. Moreover, a third dialect is also mutually intelligible with these two but has no interaction between consonants and tones at all. Svantesson and House (2006), along with describing these patterns, propose a historical source for the consonant-tone interactions they display. Nevertheless, each dialect has an independent phonology, and in this case, two of them offer valuable insight as to what is phonologically possible.

2.1 Criteria for inclusion

This survey focuses on synchronic interaction between consonants and tones. While diachronic change is, arguably, influenced by phonology, the very nature of historical reconstruction means that it is not always clear which segments are the source of tonogenesis. Thus, although I will occasionally refer to diachronic data in later chapters, I do not include such data in this chapter. Also, while I occasionally draw on data about voice quality and tone when considering the motivation for the phenomena described here, languages with tones that are distinguished by voice quality are typically not included in the survey, and those that are, are marked. One such exception is Burmese, where Lee (2007) argues that creaky voice and glottal stop both interact with tone, and although they both affect tone in the same way, they are phonologically independent of one another.

As many of the languages included in this survey are understudied, the published data on these languages rarely include phonetic measurements, nor do the field workers document whether the patterns mentioned are productive. Ultimately, this survey relies on the reports given in the works cited in Appendix A. Some of the languages and their tone patterns are described and analyzed extensively, and the linguistics community seems to have reached a degree of consensus about their phonologies. Other languages are included on the basis of a brief paragraph. It is certainly possible that later work will reveal that, for example, the Mixtec languages included here do not belong here at all; work on many other Mixtec languages considers the glottal stop to be a vowel feature or a suprasegmental feature rather than a consonant. Nevertheless, for those Mixtec languages included here, authors have argued that the glottal stops are consonants.

When there is disagreement in the literature, I typically follow the most recent or most thorough source of which I am aware. If there is some controversy about how a certain segment should be classified, I include it according to the phonetic description that is available. For example, Bradshaw (1999) includes Swati (Siswati) in her survey, grouping it with other languages where voiced obstruents and low tone interact. However, Downing and Schadeberg (2007) argue that there is no reason to classify these segments as voiced since they are never voiced phonetically in the language, nor is there an apparent voiced source historically.

Another difficulty in deciding how to classify languages is that descriptions from different traditions may describe the same phenomenon differently. Zulu would likely be classified as having more than two tones, were it spoken in Asia, though many Africanists do not treat it this way (cf. Downing & Schadeberg, 2007; Traill, Khumalo, & Fridjohn, 1987). Pike (1986) describes Carrier as a language with two tones, high and low, where consonants trigger allotonic realizations of these tones. While one linguist might attribute this to phonetic effect, another might classify Carrier as a four tone system, the tones of which are divided into high and low registers that correspond to Pike's two tones. Although there is no phonetic study included, her description implies that the differences are perceptible and persist throughout the syllable, nor is any voice quality difference listed. For these reasons, and because Pike cites a study indicating that measured allotones differ by 20%, which is certainly large enough to be a tonal difference, I include the data here.

Another confounding factor when speaking about tone, however, is that it is difficult to distinguish between phonetics and phonology. By its nature, pitch is highly variable and is affected by many factors. Microprosodic effects of consonants, intonation, stress, adjacent tones, vowel quality, and vowel duration, as well as a wide variety of extra-linguistic factors, interact to determine the pitch contour of a syllable even in non-tone languages. In tone languages, many or even all of these factors still affect the pitch of the syllable, making it difficult to determine whether a pattern is better characterized as phonetics or phonology.

It should be noted that, for all of these reasons, it is likely that not every example provided in this survey will bear up under closer scrutiny. However, most of the patterns are robust enough that this should not cast the overall results into question. Ideally, the results presented here will trigger more extensive research on the languages in question.

2.2 Which patterns are phonological?

I consider several criteria to be indicative that a pattern is likely to be active in the phonology of a language—that is, likely to be known and productively applied by the native speaker. Ideally, the pattern should hold throughout the grammar whenever the proper environment is met. However, linguists have long argued that speakers can manipulate multiple language strata that are governed by different strata, and psycholinguistic testing of Japanese speakers (Gelbert & Kawahara, 2006) shows that Japanese strata (Itô & Mester, 1995) are known to Japanese speakers. Thus, I also include some examples of languages where a pattern is consistent within a specific stratum or class of words within the grammar; these are indicated in the footnotes, where known. For example, include languages such as Carrier (Pike, 1986), where the author indicates that the phonotactic pattern "usually" holds, since there is no indication that it is lexical exception that makes up the minority case; it is entirely possible that the exceptions are triggered by post-lexical phonology or even interactions between intonation and tone. I also include languages like Kam (Long & Zheng, 1988), where there is some indication that there are exceptions to the phonotactic pattern in borrowed Chinese words.

Alternation, especially phrasal alternation, is strong evidence for phonological significance—if the same morpheme has a different realization depending on the phonological environment, then this alternation is almost certainly a part of the phonology. Those languages in which tone spreads, then, provide many opportunities to test the scope of the phonological interaction.

Some phonologists theorize that alternation is the only proof of phonology, limiting the importance of phonotactic patterns to that of historical change. However, I also include clear phonotactic patterns as part of the phonology. There is well-established precedent for this decision (Chomsky & Halle, 1965; McCarthy, 1979). Although, to my knowledge, no psycholinguistic experiments have been conducted on any of the relevant patterns in languages included in this survey, there is clear experimental evidence that native English speakers know the phonotactic patterns of their language (Bailey & Hahn, 2001; Coleman & Pierrehumbert, 1997; Frisch, Large, & Pisoni, 2000) and that knowledge of phonological categories and structure is an aid to learning phonotactics (Hayes & Wilson, To appear). Thus, there is empirical evidence supporting the idea that phonotactic knowledge is part of a speaker's competence, and consequently that the phonology should account for it. The languages included here on the basis of phonotactic evidence also meet other criteria that are typically used in establishing whether any pattern is phonological: the pattern exists across a natural class of consonants and of tones, and it is pervasive in the grammar. Although experimental data also imply that native English speakers have knowledge of gradient phonotactics and lexical biases, I typically omit languages from the survey if the only evidence for consonant-tone interaction is from the phonotactics and the phonotactic is not absolute.

This is not to say that historical forces have not shaped phonotactic patterns; certainly, they have. The Kam child, however, has no knowledge of the historical voicing posited as the source of tone lowering in her language (Edmondson, 1992) and acquires only the knowledge that an aspirated initial segment is followed by a low tone in her language. I will take the view here that this knowledge is part of the child's phonology. Further, I will argue that the she does not need to create an abstract phonological representation assigning voicing to the unvoiced tone lowering segments in order to bring this relationship in line with universal connection between low tone and voicing, but rather that the connection between aspiration and low tone is both natural and phonologically permissible.

The inclusion of phonotactic data broadens the base of languages that are considered for the survey. For example, many East and Southeast Asian languages are tonal but show few morphophonological alternations. The assumption that the phonotactic patterns in these languages are phonological is borne up by those languages in the survey that exhibit tone sandhi, that is, a specific pattern of tone alternations conditioned by an adjacent tone. In Wuyi (Bao 1999), the primary interaction between consonants and tones is phonotactic: voiced obstruents always precede the low register tones 13, 31, and 213, and voiceless obstruents, the high register tones 55, 24, and 53. The first tone in a verb-object construction or a compound undergoes sandhi. As shown by the data in (13), if the sandhi causes the tone to change register, the onset consonant undergoes a corresponding change in voicing so that the appropriate phonotactic correspondence between consonant and tone is maintained.

13. a. Low Register → High Register
   buɑ^{213} 'climb' + **s**uo^{24} 'mountain' → **p**ua^{55} suo^{24}
   zɑ^{213} 'buy' + pu^{53} 'cloth' → **s**a^{55} pu^{53}
   diŋ^{213} 'cut' + die^{31} 'electricity' → **t**iŋ^{55} die^{31}
   b. High Register → Low Register
   pie^{55} + ɦiaŋ^{213} → **b**ie^{11} ɦiaŋ^{213} 'praise'
   ka^{55} + tɕiŋ^{53} → **g**a^{11} tɕiŋ^{53} 'improve'
   kɑŋ^{55} + ɦie^{13} → **g**ɑŋ^{11} ɦie^{13} 'make a speech'

In interest of limiting the controversial status of languages in the survey, I also omit those with phonotactic patterns that, while consistent, do not apply to a natural class. For example, in Limburgian, only an acute (falling) tone is permitted before the sonorants ɳ, ŋ, and ʎ (Boersma, 2006). However, these sonorants do not form a natural class in the language, so I do not include this information in the survey, though Limburgian itself is included on the basis of other patterns. This criterion applies to tones as well. For example, San Juan Copala Trique is reported to have eight tones (Hollenbach, 1977). Of these, one cannot occur on a syllable ending in /h/, and another cannot occur on a syllable ending in a glottal stop. While a single phoneme technically should constitute a natural class, there is no apparent feature or set of features one could assign to these tones that would not also include other tones; further work on this language is necessary.

Finally, I limit the discussion here to interactions that can be categorized as high or low. Two languages, Skou (Donohue, 2003) and Xinzhai Hmong ("XTone Database Article on Xinzhai Hmong,"), are characterized as having mid tone interacting with consonants; however, this sample is too small to determine a systematic approach for dealing with these cases.

2.3 Survey results

The results in the table below summarize the types of interactions that occur between consonants and tones. I provide here only the names of the languages that are claimed to have each property. Appendix A lists the source for the data, the language family, and the country where each language is spoken. In this table, if a consonant seems to relate to the beginning of a rising tone or the end of a falling tone, it is grouped in the low tone category, and conversely, if a consonant patterns with the beginning of a falling tone or the end of a rising tone, it is placed in the high tone category.

	Affinity for L	*Affinity for H*
Voiced obstruent	Bade, Bassa, Bole, Botswana Kalanga'a, Carrier (fricative), Chinese (Wu dialects: Longyou, Shaoxing, Songjiang, Wenling, Wenzhou, Wujiang, Wuyi (voicing, voiced aspiration)), Dagara-wule, Ebrié,[6], Ewe,[7] Gbaya ɓokota, Jingpho, Kuwaa, Kotoko,[8] Lamang, Longyou Chinese, Makaa, Masa, all Mijikenda languages (9), Miya, Mulwi, Musey,[9] Nambya, Ngizim, Sayanci,[10] Suma,[11] Xhosa, Yabem, Yaka	
Voiceless obstruent	Carrier (plain voiceless)	Bade, Bassa[12], Chepang, Chinese (Wu dialects: Longyou, Shaoxing, Songjiang, Wenling, Wujiang (plain voiceless), Wuyi), Jingpho, Kammu (Western),[13] Limburgian (Maasbracht),[14] Manange (plain voiceless), Masa, Musey, Ngizim, Nupe, Rawan, Sayanci, Yabem[15]
Implosive	Kotoko, Xhosa	Bassa, Masa, Musey, Ngizim,

[6] Ebrié shows a contrast between four types of consonants, which traditionally are referred to as voiced and voiceless fortis and voiced and voiceless lenis. Only the voiced fortis series interacts with tone. Various researchers have argued that the lenis series in this or related languages should be classified as non-obstruent; see Botma and Smith (2006) and Clements and Osu (2002).

[7] There is considerable disagreement in the literature as to the extent of the consonant-tone interaction in Ewe. There may also be evidence for a connection between voiceless obstruents, sonorants, and H; see Peng (1992) and Bradshaw (1999) for discussion.

[8] The Kotoko data are quite complex; Odden (2004) discusses three lowering rules which have different consonants associated with them. The consonants listed here lower tone in the broadest category of these rules, to the exclusion of voiceless obstruents and [h]. Section 3.5 offers a partial analysis of the implosive data.

[9] The Musey patterns apply to nouns; it is less clear whether they apply to verbs (Shryock, n.d.).

[10] The mid tone in Sayanci sometimes patterns with low tones and other times with high tones, depending on grammatical context. Prenasalized obstruents pattern with high.

[11] Low tone insertion applies only in imperfective verbs in Suma (Bradshaw 1999).

[12] In Bassa, only rising and mid-low falling contour tones show an interaction with consonants. The consonants listed in the low category occur with rising tones and in the high category with falling tones; see section 3.5 for further details.

[13] Western Kammu associates voiceless unaspirated obstruents with high tone; they contrast with voiceless aspirated obstruents (Svantesson & House, 2006).

[14] Hermans and van Oostendorp (2000) argue that, although this is relationship is surface true, the phonological connection is between low tone and voicing. Boersma (2006) argues that this is a purely historical pattern.

[15] Hansson 2004 argues that the phonology need not refer to a [-voice] feature to account for this pattern.

		Sayanci
Sonorant	Kotoko, Wujiang Chinese	Bassa, Musey, Sayanci
Voiceless aspiration, voiceless fricative, /h/[16]	Bassa (/h/), Botswana Kalanga'a (aspiration),[17] Jingpho (ħ),[18] Kam (aspiration)[19], Kangri (/h/), Kickapoo (fricative, aspiration), Manange (aspiration),[20] Mulao (aspiration), Nambya (/F/),[21] Shaoxing Chinese (/h/), Wujiang Chinese (aspiration)	Carrier (aspiration, fricative), Northern Kammu (aspiration), Korean (aspiration), [22] Thakali (aspiration)[23], Highland Yao (aspiration)
Glottal/ Glottalized (nonimplosive)	Carrier (ʔ, word initial), Cherokee (ʔ), Kam (glottalized stop), Kiowa (ʔ), Kotoko (ʔ), San Miguel el Grande Mixtec (ʔ), Sanuma (ʔ), Sekani (ʔ), Thai (glottalized stop), Tuwuli (ʔ), Wanano (ʔ)[24], Zahao (ʔ)[25]	Amuzgo (ʔ), Ayutla Mixtec (ʔ), Burmese (ʔ), Carrier (ʔ, word final; ejective), Kachari (ʔ), Moro (ʔ), Shaoxing Chinese (ʔ), Wuyi Chinese (glottalized sonorant)
Stiff/Tense		Korean
Slack/Lax	Korean, Swati, Zulu	

Table 2. Languages with Consonant-Tone Interaction

2.3.1 Summary of survey

[16] This includes only those languages where these segments do not pattern with voiceless obstruents as expected. A language like Bade, where it is clear that the relevant contrast is between voiced and voiceless stops, is categorized with the voiceless obstruent group even though these obstruents are aspirated.

[17] These contrast with a second set of non-depressor aspirated stops; the aspiration has longer duration in the depressors (Downing & Gick, 2001).

[18] Maran (1971) describes this sound as "very heavily aspirated with tongue root lowered and backed against the pharyngeal wall" (p. 173); this contrasts with /h/, which groups with the voiceless obstruents and H.

[19] More specifically, there is a relationship between aspiration and rising tones; see Section 3.4 for an analysis.

[20] This is limited to falling tones on monosyllabic words (Hildebrandt, 2003).

[21] This contrasts with a non-depressor /f/; the depressor has longer duration (Downing & Gick, 2001).

[22] Various linguists studying Korean dialects have proposed that the feature [+stiff] should include both voiceless aspirated stops and voiceless tense stops, both of which trigger high tone insertion, and both of which contrast with a third set of consonants that is voiceless unaspirated in the position where the tone interaction occurs. See Silva (2006) for details.

[23] Thakali combines voice register and tone; voiceless aspirated onsets appear before high, tense vowels (Hari, 1971). I include the example here because tone and register contrast after voiceless unaspirated consonants in the language, suggesting that register does not drive the consonant distinction.

[24] According to Stenzel (2007), this is a strong tendency, but not absolute.

[25] Rising tone cannot precede a glottal stop in Zahao (Yip, 1982).

The data in Table 2 cover 68 dialects and more than 54 languages.[26] In these languages, it is found that the correlations between voicing and low tone and voicelessness and high tone are nearly absolute across languages. The numbers of languages displaying these correlations are quite different, though, with considerably more languages having a connection between voicing and low tone (38) than between voicelessness and high tone (17). Carrier appears to be an exception; however, categorizing it as having a correlation between voiceless obstruents and low tone is somewhat misleading, since the stops in Carrier contrast, not in voicing, but in aspiration: voiceless unaspirated stops precede lower tones than voiceless aspirated stops do.

Although it has frequently been claimed that [voice] is the only feature that can interact with tone, the large number of languages that show evidence for another consonant type interacting with tone shows that such a claim is too narrow. Not only is there strong synchronic evidence that this is so, but there is also significant diachronic evidence to this effect. For example, Chen (2000) summarizes the Asian tonogenesis literature, stating that a total of 111 Sino-Tibetan languages show historical tone splits triggered by aspiration.[27]

While the sample of languages where a stiff/slack opposition is claimed to interact with tone is small, these also show a consistent correlation between lax and low, and correspondingly, between tense and high.

However, the data for other types of consonants is less clear. Sonorants, though modally voiced, are usually considered to be phonologically unmarked for [voice], which may be the reason only five languages in the survey show an

[26] The exact number, of course, depends on whose definition of dialect is followed.
[27] Chen includes Kam-Tai and Miao-Yao in Sino-Tibetan.

interaction between sonorant consonants and tone. Nevertheless, these five languages are split: two show an interaction between sonorants and low tone, while the other three show an interaction between sonorants and high tone. In this sense, sonorants pattern better with the other consonant types that do not show an absolute correlation with a specific type of tone. Implosives, while often neutral with regard to consonant-tone interaction, also interact with both high and low tone.

I group voiceless aspiration, voiceless frication, and /h/ together since they have some phonetic similarity and since Carrier and Kickapoo show identical tone patterns for aspiration and voiceless fricatives. Although the languages in this category show some tendency to pattern with low tone, they are clearly divided. Moreover, if aspiration is considered incidental in a basic contrast between voiced and voiceless stops, the language is placed in the voiceless category rather than the voiceless aspiration category; this may result in skewed data. Finally, non-implosive glottalized sounds pattern almost equally often with low and high tones.

In Chapter 3 I return to these patterns and consider what type of constraint system is necessary to account for them. However, it is clear that it is not possible to attribute all consonant-tone interaction to shared features between consonants and laryngeal features. Even if one were to assign low tone glottals a different feature than high tone glottals, this feature is unlikely to be [voice]. Furthermore, such a feature would in essence equate glottalization, voiceless aspiration, voicing, and laxness, or at the very least, assign them to the same natural class, one that would oppose voicelessness and tenseness along with the high tone version of glottalization and voiceless aspiration. There is no evidence independent of tone interaction that this is a desirable result. Rather, I propose that all laryngeal features be permitted to interact with tone.

2.3.2 Types of interactions

The ways in which consonants and tones interact also vary considerably from language to language. Often, a language where tones are highly mobile will display multiple types of interactions, thus reinforcing the evidence that consonant-tone interaction is phonologically active in that language. For example, consonants block tone spreading in Bade, but they also affect the way tone is assigned to verbs, limit the occurrence of falling tone, and trigger downstep, as shown in Chapter 3. The interaction in Wuyi is primarily phonotactic, but as shown in (13), a change in tone triggers a change in consonant voicing. This adds Wuyi to the small group of languages in which there is evidence that tone is able to affect consonants, rather than the reverse (see Maddieson, 1978). Consonants also trigger tone shift in Xhosa (Cassimjee, 1998), for example, and affect the docking of a floating tone in, e.g., San Miguel el Grande Mixtec (Tranel, 1995). The breadth of interaction, then, seems to cover the range of tonal phonology.

2.3.3 Types of tones

The density of tone assignment varies considerably from language to language, and it is probably more accurate to look at this variation as belonging to a continuum of lexical tone types rather than attempting a strict division between lexical tone and pitch accent (Hyman, 2007). The majority of the languages included in Table 2 fall somewhere on this continuum, with languages such as Wuyi typically assigning one tone per syllable, and languages such as Carrier demonstrating a classic pitch accent pattern.

While general analysis practices make it difficult to compare data from languages spoken in different regions, it is clear that both level tones and contour tones interact with consonants. In particular, this is possible even within one language: the Kam tones are divided according to register, and glottal stop affects register, but within those registers, various level and contour tones exist, and of those, the rising tones interact with aspiration (see 3.4 for details). While it does seem more common for consonants to interact with register tone, especially if two tone and three tone systems are classified as register tone systems, interactions between consonants and contour or level tones within a register are arguably found in Carrier, Manange, Kiowa, and Wenzhou Chinese.

However, at least two languages[28] display interactions between post-lexical tone and consonants. One is Seoul Korean, previously discussed in Section 1.1. The second is Sanuma (Borgman 1990). Although the Sanuma data are not thoroughly described, the existing description is intriguing. Borgman specifically states that glottal stop co-occurs with non-rising intonation in one case: although pitch generally rises on the last syllable of a subordinate clause, when the clause is marked with the clitic –ka, there is no rising intonation, and the clause is followed by a glottal stop. Glottal stops also typically follow a declarative utterance but never follow an interrogative utterance. Though Borgman does not provide any details about the intonation of these utterances, it is quite common cross-linguistically for an intonational high tone to mark an interrogative; if this is the case in Sanuma, then the glottal stop is again associated with a non-rising intonation curve. There are several types of declaratives that are not followed by a glottal stop, and these also fit into well-defined categories, though again, no details are provided about intonation:

[28] A possible third example is Chrau (Thomas, 1966), where intonation is reported to rise at the end of a phrase where the final syllable ends in a voiceless obstruent and fall if the syllable ends in a voiced obstruent. However, this may be attributable to duration differences before a voiceless obstruent (Hombert, Ohala, & Ewan, 1979).

Glottal stop does not occur after some verification particles and interjections, verbs in a special narrative form, or a bare noun, which is a stative.

The fact that consonant-tone interaction is possible even at the post-lexical level, together with the fact that there seems to be no distinction between register tones, contour tones, or level tones in terms of types of interaction, strongly implies that tone features are generic with regard to tone type. For example, this implies that Yip's (1995) proposal, in which the feature geometry limits consonant-tone interaction by directly relating tone register to laryngeal features, cannot be correct. The relationship between consonant and tone must be structurally more abstract.

2.3.4 A note on the distribution of languages

It is, I think, not possible to determine from this survey whether consonant-tone interaction could be considered an areal feature. Certainly, there are areas where it seems that many languages representing multiple families have this feature, for example, southern Africa or Nigeria. However, in many cases, it is impossible to know whether the exclusion of a language from the survey actually means that nearby languages lack a phonological interaction between consonant and tone. For example, there are many tonal languages spoken on the island of New Guinea, and the languages spoken there represent at least two major families—Austronesian and Trans New Guinea—but only one language from Papua New Guinea is included in the survey. However, few detailed phonological descriptions of the neighboring languages are available, and language density is extremely high, so even if consonant-tone interaction is common in the area Yabem is spoken, it would still be overlooked as an aerial feature of the languages there.

Nevertheless, the languages are distributed across enough language families and regions that it is clear that these data cannot all result from inherited properties or language contact.

2.4 Summary

The data presented in this survey form the basis for the remaining chapters of this dissertation, in which I will discuss why the patterns listed here occur, and, equally importantly, why those that are not listed here do not. It has been shown that there is considerable variation in which types of laryngeal features interact with tone, and what types of tones they interact with. Nevertheless, I will argue that this variation is quite principled according to phonetic considerations and that it can be accounted for using phonetically grounded constraints.

Chapter 3 Phonological Approaches

This chapter explores a phonological approach to consonant-tone interaction. To this end, I provide an in-depth look at two languages, Bade and Kam, in conjunction with a general account of the data in Chapter 2. I introduce the concept of the tone span as a way of relating two features such as voice and low that, I argue, are otherwise structurally unrelated, though I provide evidence that tone and other laryngeal features are phonetically related.

3.1 Spans and constraints on them

I argue here that a theory of consonant-tone interaction requires the two sounds to stand in some natural relationship to one another, whether articulatory (cf. Flemming 2004) or perceptual (cf. Steriade 2001 and many others), but that they need not, and in fact do not, share a specific feature. For example, voice and tone interact because they share phonetic properties, permitting a constraint to relate the two, and not because they share a feature. In arguing for this analysis, I provide a phonetically based and phonologically precise theory of consonant-tone interaction that relies on two concepts: first, a phonetically motivated tone span (cf. Cassimjee & Kisseberth, 1998; Cole & Kisseberth, 1994; McCarthy, 2004; Smolensky, 2006), and second, constraints against specific laryngeal features coinciding with a specific tone span. These constraints are most similar to the pre-Optimality Theory grounding constraints proposed by Peng (1992) and to Hansson's (2004) approach to Yabem.

Following the basic presuppositions of phonology, I assume that in order for consonants and tones to interact with one another, they must share some common property. Specifically, they share a common articulator: the larynx. Thus, most consonants have a specific effect on the F0 value of a following vowel; this is referred to as microprosody and is addressed in the following section. In some languages, this microprosodic effect continues throughout much of the vowel. Although many consonants are too low in intensity to carry perceptible tone, I hypothesize that articulatory gestures necessary for producing a phonologically identical sequence of high or low tones may also affect the gestures of the larynx during the intervening consonant, or vice versa. It is this articulatory continuity that underlies the concept of a tone span as the point of interaction between consonants and tone.

Conceptually, the span of a tone consists of all segments in its temporal domain; it is that which links tones to segments. Since the quantitative tone duration has no phonological representation, the formal definition of span refers instead to linearity:

14. A segment *a* is in the **span** of a tone *T* if
    (i) *a* is associated to *T*, or
    (ii) *b* and *c* are associated to *T* and $b < a < c$[29]

Consequently, each segment that is associated with a tone is also contained in a span. However, this definition does not require each segment in a word to be contained in a tone span. A span is further constrained as follows:

15. A span cannot be empty.

Since a span is defined over segments, not tones, (15) means that a floating tone cannot be contained in a span.

I further assume that spans for the same tone type are organized linearly and, at least in the data examined in this chapter, do not overlap. For example, two contour spans should have no shared material in their domains, though a contour span will

[29] This definition ensures that tone spans are *convex* in the sense of Bird and Klein (1990).

share a domain with a register span in languages where both are utilized: a low falling tone over two moras has a single low register tone but two distinct contour tones, high and low. I do not consider any languages here that require two spans to include a single mora.

16.

```
 L          H
 |\         |
 μ    μ     μ
 |    |     |
ɗ[uwa]L ɬ[u]H
```

The figure in (16) compares an autosegmental representation of the word *ɗùwàlú* to its representation in terms of tone spans. Here, since the low tone has spread from the [u] to the [a] over the intervening [w], the span of the low tone is [uwa], while the high tone span consists only of the segment [u]. I represent the domain of a span by using brackets with subscripted tones; thus, the tone spans corresponding to (16) are denoted ɗ[uwa]$_{L}$ɬ[u]$_{H}$. I assume that in Bade, the default tone spans include only the syllable rhyme; onsets are included in the span only in the case that a tone spreads over them. However, this is likely not the case in all languages. Recent studies suggest that languages may differ phonetically in regard to the domain of the tone; Xu and Liu (2006) argue that the phonetic domain of the tone is the entire syllable in Mandarin Chinese, while Morén and Zsiga (2006) argue that the phonetic domain of the tone is the mora in Thai.

In Chapter 4, I address the question of how the span is interpreted by the phonetics. It is expected that all segments included in the boundaries of a span will be appropriately modified according to the feature value expressed by the span. That is, the larynx is should maintain a setting during obstruent pronunciation that is as close as possible to one required for the tone span in which it are included. While this cannot be directly tested for obstruents, it is possible to test whether the pitch curve on the vowel differs depending on whether a preceding obstruent is in the same span. For sonorants, it is possible to directly test whether their F0 value is modified when they are included in a span.

A tone span does not, in and of itself, require specific assumptions about the nature of the TBU. Yip (2002), in her survey of tone languages, concludes that languages differ in their phonology as to whether the TBU is the syllable or the mora. This is somewhat parallel to a cross-linguistic difference in whether a syllable weight distinction is relevant in a stress system. Nevertheless, if, as I assume here, a contour tone is phonologically represented by a sequence of high and low tone spans, then the minimal tone span is not directly equivalent to the TBU since some languages permit contour tones even on monomoraic syllables. I take the approach here that constraints determine the minimal span in a given language, and that this minimal span may be a prosodic unit rather than a segmental one.

Since each span must, by definition, contain at least one TBU (see 15), this means that, in Bade, where the TBU is the mora, the minimal tone span is likewise one mora. Consequently, the smallest possible tone span in Bade excludes the syllable onset, permitting the parsing ɗ$[\text{uwa}]_L$ɬ$[\text{u}]_H$ shown in (16). On the other hand, in a language where the TBU is the syllable, the minimal tone span is also the syllable. In such a language, the default parsing of (16) would include all the consonants in its two tone spans, $[\text{ɗuwa}]_L$ and $[\text{ɬu}]_H$.

The ability to exclude the syllable onset from the tone span will prove crucial for the analysis of Bade, provided in Section 3.3; it is only when a tone spreads over a consonant, thereby requiring that consonant to participate in its span, that specific onsets are prohibited. For example, a low tone cannot spread to the second syllable of the word *là:kí* ‘small’, even in an environment where low tone would otherwise spread, because it cannot include the voiceless [k] in its span; *l[aki]$_L$ is ungrammatical. However, in the word *kàbí:n* ‘mat’, a low tone is permitted to follow a [k] since, in terms of tone spans, this word is parsed k[a]$_L$b[i:n]$_H$. Similarly, since tone spans are not defined in terms of sequences of identical tones, the word *gàtàvén* ‘senna’ is assumed to consist of three tone spans, g[a]$_L$t[a]$_L$v[en]$_H$. Thus, the difference between lexically permitted sequences and blocked spreading sequences results from a difference in structure.

It is implicitly assumed here that spans can be marked in the input, and further, that this is necessary in the case of non-predictable surface tone alignment. It is further assumed that an unpronounced tone, i.e. a floating tone, has no span associated with it since there is no segment on which a floating tone is realized. Some examples of potential span alignments are included in Table 3.

Pattern	Span representation	Comments
One tone per syllable, onsets excluded; one tone includes multiple moras	$p[au]_L m[u]_H b[an]_L$	This is the default for level tones in Bade
One tone per mora	$p[a]_H[u]_L m[u]_H b[a]_H[n]_L$	This is how contour tones are represented in Bade
One tone is shared across several syllables	$p[aumuban]_L$	I assume adjacent identical tones in a word typically have this representation in Bade
One tone per syllable, onsets included	$[pau]_L[mu]_H[ban]_L$	Phonotactic onset-tone interaction requires this type of representation; see section 3.4 on Kam
Two tones on one mora	$p[au]_L m[u]_H[u]_L b[an]_L$ \/ μ	The falling tone occurs on one mora; this is difficult to represent graphically, but conceptually, the span need not be aligned to a specific prosodic or segmental entity; see 3.4

Table 3. Examples of span alignment

The research here focuses on consonant-tone interaction rather than on the formal representation of tone, and it is not intended to provide a complete theory of tone spans beyond what is needed to account for consonant-tone interaction. Nevertheless, it is useful to briefly compare the model assumed here with similar ideas in the literature. Although it bears strong similarities to them, especially conceptually, the use of the term span in this paper does not necessitate the same assumptions as the technical use of the term span in Span Theory (McCarthy, 2004) or domain in Optimal Domains Theory (Cole and Kisseberth, 1994, Cassimjee and Kisseberth, 1998) or feature domain (Smolensky, 2006). In particular, the idea of the span's head does not enter into the present research in this paper, while it is an essential part of the theory for the others. Also, the idea of a span that is presented here differs from Optimal Domains Theory in that it requires all vowels in the span to have the same tone.

Since neither McCarthy nor Smolensky specifically address tone spans, their systems are more difficult to compare with the one used here. For McCarthy, blocking of feature spreading is achieved through the interaction of an OCP-type constraint banning adjacent spans with a series of universally-ranked constraints requiring various types of segments to head spans. This type of universal ranking cannot be obviously extended to a tone system where both high and low tones spread but are blocked by different types of obstruents. Smolensky's approach is largely concerned with vowel harmony and requires local conjunction of markedness and faithfulness constraints, in addition to headedness, to achieve the correct harmony results; this paper, again, addresses a quite different issue, where the blocking results from an intervening consonant, in a different fashion.

3.1.2 Constraints for consonant-tone interaction

Tone spans are useful in exploring consonant-tone interaction because, unlike autosegmental representations, they assume that a phonological relationship between consonants and tones is possible even if there is no direct structural connection between the consonant and the tone.

Conceptually, despite the fact that pitch is not audibly realized on an obstruent, the vocal folds will remain closer to their setting for the surrounding vowels during the obstruent closure if this intervening consonant does not require a drastically different vocal fold setting. Thus, the sequence *ábá*, with two high-toned vowels interrupted by a voiced obstruent, is articulatorily dispreferred because voicing corresponds to a laryngeal setting that results in low F0. The sequence *àbà*, on the other hand, is preferred because the larynx requires less adjustment to transition from a low F0 on a vowel to a voiced [b] and back to a low F0. Outside the realm of tone, a similar effect has been documented in Turkish rounding harmony, where the lips remain rounded for consonants that occur between two round vowels (Boyce, 1990), suggesting that, articulatorily, the rounding harmony is realized on the intervening consonant as well as on the vowels. In Hungarian vowel harmony, the transparent vowels [i] and [i:] show a difference in retraction in front and back harmony environments, again showing articulatory continuity across a segment that is not permitted to harmonize phonologically (Benus and Gafos, 2007). Such a claim is certainly phonetically plausible for tone as well, since studies such as Xu and Liu (in press) have shown that, in Mandarin Chinese, the tone is phonetically aligned to the syllable; that is, a speaker begins to move towards a tonal target at the syllable onset, even if the pitch is not audible on that segment.

Thus, the phonetic motivation for the consonant-tone constraints lies in the movement of the larynx and the interaction between laryngeal features and pitch. Consequently, the constraints introduced here are, in essence, constraints requiring compatible laryngeal settings or constraints against contradictory laryngeal settings. The constraints will take the basic form of x → y, if x then y, where x and y are compatible laryngeal features, such as [+voice] and [low], or x → ¬y, if x then not y, where x and y are incompatible laryngeal features such as [-voice] and [low]. The latter constraint type is necessary in the case that there is underspecification or a ternary distinction, such as a three tone system with high, mid, and low tones.

However, the phonetic basis for all constraints relating, e.g., H with [-vce] or H with ¬[+vce] is the same, that of the phonetic similarity between voicelessness and high F0. Specifically, then, by blocking low tone spreading, voiceless obstruents actually demonstrate an affinity for high tone. More generally, a consonant blocks spreading when it is sufficiently *unlike* the tone it blocks. Further, in a language where consonants interact with tone, spreading is permitted by a consonant that is sufficiently *like* the tone that spreads; a consonant has an affinity for such a tone. In 3.3, I show that voiceless obstruents block low tone spreading in Bade, meaning they must be sufficiently unlike low tone in the language. Since Bade has only two tones, and since voiceless obstruents permit high tone to spread, I assume, then, that they have an affinity for high tone.

This view has the benefit of maintaining phonological consistency. In the languages in Bradshaw's (1999) survey, voiced obstruents consistently block high tone spreading; they also cause tone lowering and trigger low tone insertion. If all of these are effects of an affinity between low tone and voicing, then a simple underlying phonetic motivation for a single phonological behavior is possible, as Bradshaw demonstrates.

3.2 The Phonetics of Consonant-Tone Interaction

In this section, I provide an overview of the literature on the production of F0 and the phonetic relationship between consonants and F0. The majority of this section focuses on F0 manipulation, voicing, and their relationship to one another, since these topics have been most thoroughly researched, but I also provide a summary of the literature about the phonetic relationship between F0 and other types of laryngeal features.

3.2.1 Voicing and F0

House and Fairbanks (1953) are perhaps the first to demonstrate conclusively a correlation between the voicing of a consonant and the fundamental frequency of the following vowel. In their study, they show that the F0 of a vowel occurring in a syllable beginning and ending with voiced /m n b d g v z/, as pronounced by English speakers in nonsense words, is significantly lower than the F0 of vowels between /p t k f s/. It is not clear from House and Fairbanks' experiment that voicing is the relevant trigger for the difference between /b d g/ and /p t k/; since all syllables in their experiment are stressed and followed an open syllable, they contrast in aspiration as well as voicing. However, Ohde (1984) demonstrates that voicing is the relevant difference for English; in a medial context, F0 is significantly higher following both voiceless aspirated and voiceless unaspirated stops (in clusters) than it is following voiced stops. He also shows that in the first glottal period following voicing onset, F0 is significantly higher for voiceless unaspirated stops than for voiceless aspirated stops, but following this the difference disappears.

The basic result of these and similar papers, that F0 is higher following voiceless obstruents than voiced ones, has been replicated in experiments in a number of languages, including French (Hombert, 1978), Russian (Chistovich, 1969), Ikwere (Clements & Osu, 2002), and Zulu (Traill, Khumalo, & Fridjohn, 1987) (see Moreton, 2006 for summary), to the point that Maddieson (1997) includes it in his list of phonetic universals. Although some have suggested that a fall in F0 following a voiceless consonant versus an F0 rise following a voiced obstruent is actually the perceptually relevant difference, Ohde (1984) shows that, in at least in some environments, English F0 falls after both voiced and voiceless obstruents. Svantesson and House (2006) also show that, at least in the frame they used, F0 falls after both voiced and voiceless segments in Eastern Kammu, but the fall is greater after voiceless segments than voiced ones, implying that the general pattern of voiceless > voiced still holds.

3.2.2 The physiology of the larynx

In order to understand why voicing and fundamental frequency should be related, it is first necessary to understand how each of them is controlled. Except where otherwise indicated, the following summary of laryngeal physiology is based on Stevens (1998). The summary also includes data from Atkinson (1978), a study of which muscle movements have the highest correlation to F0 movement at different pitch ranges.

Most important to both voicing and F0 are the vocal folds, located in the larynx, which consist of two bands of tissue, 1.0-1.5 cm long and 2-3 mm thick in an adult. They are attached approximately parallel to each other in an anterior-posterior direction. The fundamental frequency of vocal fold vibration is primarily determined by the tension or stiffness of the vocal folds, though the thickness of the vocal folds also affects F0. However, since the vocal folds themselves are not muscles, they cannot manipulate these factors. Instead, the change results from the movements of various muscles, and through these, the manipulation of the four laryngeal cartilages, the thyroid, the cricoid, and the arytenoids.

The anterior ends of the vocal folds are connected to the anterior commissure of the thyroid cartilage, which is located at the inner surface of its angle, and the posterior ends of the vocal folds are connected to the anterior corners and medial margins of the arytenoid cartilages. The arytenoid cartilages, in turn, are mounted on the cricoid cartilage and can tilt from side to side or slide along the edges of the cricoid cartilage. The lower vertical projections of the thyroid cartilage likewise articulate with the cricoid cartilage; the thyroid cartilage can both rotate and rock with respect to the cricoid cartilage. Thus, the downward movement of the anterior thyroid cartilage with respect to the cricoid cartilage stretches the vocal folds. Specifically, a 1 mm downward movement decreases the angle between the two cartilages by 2-3 degrees, and this change in tilt lengthens the vocal folds by about .5 mm, or approximately 3-5 percent. The maximum variation in vocal fold length for speech production is probably about 3 mm for adults (Stevens, 1998). These adjustments will ultimately affect the fundamental frequency at which the vocal folds vibrate.

The inferior portion of the cricoid cartilage attaches the larynx to the trachea. The top portion of the larynx is connected to the hyoid bone; more specifically, ligaments attach the superior prominences of the thyroid cartilage to the posterior ends of the projections of the hyoid bone, which in turn is connected to the jaw and skull. Thus, movements of these structures can also ultimately affect the position of the vocal folds.

A number of muscles act to change the position and mechanical properties of the vocal folds. The cricothyroid muscle connects the cricoid cartilage to the thyroid cartilage, filling the space between them. It acts in multiple ways. When the anterior portion contracts, this causes the thyroid cartilage to rotate with respect to the cricoid cartilage, thereby tilting the cricoid cartilage backwards and lengthening and stretching the vocal folds. This increases tension in the vocal folds while at the same time reducing mass per length; these combine to result in a higher F0. When the posterior portion of the cricothyroid muscle contracts, this also stretches the vocal folds, possibly by translating the thyroid cartilage with respect to the cricoid cartilage. Stevens cites Fujisaki (1992) as proposing that the difference between these two types of motion is the speed at which they occur; the change in vocal fold stiffness from translation via posterior contraction is slower than the change resulting from rotation via anterior contraction. Fujisaki then proposes that these have two different roles in speech. Atkinson (1978) finds that the cricothyroid muscle shows the highest overall correlation to change in F0 among the muscles in his study; the correlation is positive and is evident for both raising and lowering F0. However, while it is the most important factor contributing to F0 movement for high F0, there is only low correlation at mid and low F0.[30]

A second set of relevant muscles are the posterior cricoarytenoid muscles. This pair of muscles connects each side of the posterior surface of the cricoid cartilage to the muscular process of each arytenoid cartilage at its lateral projection. When these muscles contract, the vocal folds are abducted. At the same time, the arytenoid cartilages are tilted back, which typically lengthens the vocal folds, thereby increasing their stiffness, which in turn, increases F0.

The interarytenoid muscle connects the two arytenoids cartilages to each other and is attached to their posterior surfaces. When this muscle contracts, it brings the arytenoids together and consequently also adducts the posterior ends of the vocal folds.

The lateral cricoarytenoid muscle is attached to the muscular process of the arytenoids and the lateral surface of the cricoid. This adducts the arytenoids and rotates them, complementing the function of the interarytenoid muscle. According to Atkinson's study, the lateral cricoarytenoid muscle is never the dominant factor in F0 control. However, it has a high overall correlation with F0; in particular, it is very

[30] In this study, high, mid, and low F0 refer to normal speech range; for this speaker high is 120-160 Hz, mid is 100-120 Hz, and low is less than 100 Hz.

active for rising F0 and shows little activity for falling F0. There is moderate correlation with high F0, lower for low F0, and none for mid-range F0. Atkinson also points out that, whenever the cricoarytenoid correlates with F0, it also correlates with cricothyroid activity. Thus, he suggests that its role may be to compensate for the cricothyroid action; possibly it serves to maintain medial compression of the vocal folds rather than to directly control F0. Since the lateral cricoarytenoid muscles adduct the vocal folds, thereby reducing the effective length, this results in a higher pitch. It is also possible that the contraction of the posterior cricoarytenoid muscle causes a rise in F0 by pulling the arytenoids backward, thereby stretching the vocal folds, though other muscles must contribute to this if the vocal folds are to remain in a position where voicing can occur.

The thyroarytenoid muscle, attached to the thyroid and the arytenoids, is located lateral to the surfaces of each of the vocal folds. It consists of two components, the lateral component, known as the lateralis, which adducts the vocal folds, and the medial component, known as the vocalis. When the vocalis contracts, the movement shortens and thickens the vocal folds and appears to increase their tension and stiffness. The vocalis muscle shows a moderate correlation to F0 overall and does so consistently in Atkinson's study; there is little difference for pitch movement or range. He suggests that this is primarily synergistic activity with the cricothyroid and cricoarytenoid muscles, though Clark and Yallop (1995) add that the vocalis and thyroarytenoid muscles may be antagonistic to the action of the cricothyroid muscle in that they shorten the vocal folds and reduce tension.

Finally, the larynx itself may be displaced in such a way as to affect the length of the vocal folds, thereby changing the tension. This displacement is caused by the action of extrinsic laryngeal muscles. The sternohyoid and sternothyroid muscles attach the hyoid bone and the thyroid cartilage, respectively, to the part of the sternum below the larynx. When they contract, they pull the larynx downward. According to Atkinson (1978), the sternohyoid muscle shows a high negative correlation with F0; it is the most important factor in controlling pitch for mid range F0 but shows low correlation in the low and high ranges. It is equally relevant for rising and falling pitch. One explanation of this effect is provided in Honda (2004). As the larynx moves downward, the cricoid cartilage moves downward along the cervical spine; since the spine is curved in this region, this causes the anterior surface of the cricoid to tilt forward. This increases the angle between the thyroid and cricoid, thereby decreasing vocal fold length and, consequently, decreasing vocal fold stiffness and tension as well. The final result is lowered fundamental frequency. However, there seems to be some disagreement as to whether this is the actual cause; Stevens (1998) cites Honda but also cites Sonninen (1968) as proposing that the position of the sternothyroid muscle on the thyroid cartilage is such that, when it contracts, in addition to lowering the larynx, it also causes the thyroid cartilage to tilt upward in relation to the cricoid. In the end, though, the effect is the same; fundamental frequency is lowered through the same changes in vocal fold length and tension that Honda describes.

Finally, the cricopharyngeus muscle, attached to the cricoid cartilage, the hyoid bone, and the pharynx, can also serve to tilt the cricoid cartilage downward with the same lowering effects on fundamental frequency. The stylohyoid muscle and the anterior and posterior bellies of the digastric muscle attach the hyoid bone to styloid and mastoid processes of the temporal bone (in the skull) and the anterior portion of the mandible. The contraction of these muscles sometimes has the secondary effect of raising the larynx. In addition, Clark and Yallop (1995) state that the infrahyoidal strap muscle “may complement relaxation of the cricothyroid in pitch lowering” (p. 190).

In addition to muscular activity, there is also a correlation between subglottal pressure and F0. Overall, subglottal pressure shows a lower correlation with F0 than any of the muscles in the Atkinson study. However, this depends on condition; for statements, subglottal pressure is the most highly correlated factor, whereas in questions, there is no correlation at all. In addition, subglottal pressure is the highest correlate with F0 in the low F0 range but is not significant for mid or high F0. In general, lower intraoral pressure (such as that resulting from an obstruent) leads to lower transglottal airflow and this in turn lowers F0.

3.2.3 Relevance to phonology

Atkinson concludes from his study that there are at least two distinct laryngeal states for speech; in each state a different set of physiological factors is primarily relevant for F0 control. In one state, the high range, the vocal folds must be long, thin, and taut, all of which increase the rate of vocal fold vibration; the activity of the cricothyroid muscle seems most relevant to creating this condition. In the low range, the vocal folds must be short, thick, and slack, all of which decrease vocal fold vibration; here, subglottal pressure shows the highest correlation to F0. It is possible that such ranges could form a phonetic basis for register tone.

However, it is clear from this summary that there is no one muscular action that corresponds to F0 control, or even to a specific type of F0 control. Although certain muscles (or other factors) dominate for specific types of F0 control, a number of muscles work together to achieve this result. Although this is unsurprising from a physiological perspective, it is relevant to phonological theory in that it shows that there is not a one-to-one correlation between F0 features and a specific laryngeal gesture; the phonology must be more abstract than this.

Nevertheless, according to Honda's (2004) survey, the variation in physiological cause of F0 control is partly due to different types of F0 manipulation: segmental control (i.e. accent; presumably this extends to lexical tone), global control (i.e. declination), and microprosody have physiological causes that are separate to some degree.

Segmental F0, in Honda's sense, is controlled primarily by the laryngeal muscles. In particular, the cricothyroid muscle contracts to raise F0, as explained above. The primary cause of lowered pitch, on the other hand, seems to be the relaxation of the cricothyroid muscle; this "resets vocal fold tension," and F0 falls. Honda also states that some of the strap muscles, and in particular the sternohyoid muscle, are active as F0 falls; presumably, then, they are in part responsible for lowered F0.

For microprosody, on the other hand, Honda suggests that the correlations between voicing and low F0 and voicelessness and high F0 lie in the fact that the larynx and hyoid bone are lower for voiced stops than voiceless ones, and a lowered larynx results in lower pitch. F0 raising, on the other hand, Honda attributes to the activity of the cricothyroid muscle; the cricothyroid muscle applies "a sudden stretch to the vocal folds" in order to stop vocal fold vibration for a voiceless stop, and consequently, F0 is higher after a voiceless obstruent.

According to Honda's summary, then, raised F0 seems to have the same basic physiological explanation whether it is realizing high tone or it is simply the pitch perturbation resulting from a voiceless consonant. Lowered F0, on the other hand, seems to have two independent causes for lexical tone and microprosody. Again, this does not translate directly into to articulatory phonology; the prediction, if this were the case, would be that voiceless consonants would phonologically cause tone raising but that voiced consonants would not cause tone lowering, but in fact the opposite correlation is more frequent. In the following section, I survey further hypotheses about the physiology of voicing and its relationship to F0.

3.2.4 Voicing

In order to make sense of the relationship between fundamental frequency and voicing, it is also necessary to understand the physiological factors that cause an obstruent to be voiced or voiceless. In order for an obstruent to be voiced, the vocal folds must be in a state such that they can vibrate during at least part of the interval when the vocal tract obstruction occurs. Thus, the vocal folds must be adducted, and the tension of the vocal folds must be adjusted appropriately. It is also necessary that there be airflow through the glottis from the lungs in order to maintain maintain vocal fold vibration. For an oral stop, since air is not allowed to escape through the mouth or the nose, either the laryngeal configuration or the supraglottal volume must increase to allow air to continue to flow. This volume increase may be achieved by several changes: lowering the larynx with the sternohyoid and sternothyroid muscles, expanding pharyngeal volume (by advancing the tongue root and epiglottis), and raising the soft palate. These, in turn, require or result in other laryngeal adjustments. In order to allow expansion of the vocal tract, the vocal tract walls decrease in stiffness. Moreover, when the larynx lowers, the vocal folds are shortened, as described above. This results in an increase in slackness, which allows the vocal folds to vibrate more easily. Thus, there are multiple articulatory factors that can combine to produce a voiced obstruent.[31]

Since these adjustments affect the vocal folds, they also affect F0. The connection between lowered larynx and lowered F0 was already outlined in the previous section. Stevens (1998), too, supports this explanation for F0 lowering. Based on physiological data, he calculates that the larynx is 4-6 mm lower for voiced stops than for voiceless ones; this results in the vocal folds being 2-3% shorter, which decreases stiffness by 9-15%. This, in turn, lowers F0 5-7% in the onset of the following vowel. In fact, F0 lowering appears to be greater than this, in the range of 10-15% less than the F0 following a voiceless stop. Stevens suggests, however, that this greater-than-expected difference results from the fact that there is an increase in F0 following the voiceless stop.

The lower F0 associated with voicing may result from the aerodynamic conditions caused by the supraglottal constriction, especially in the case of nasals and laterals. The decreased stiffness of the vocal tract walls and vocal folds leads to a decrease in rate of vibration. Stevens also indicates that the frequency of vibration will decrease during the stop closure due to the reduced transglottal pressure that results from the oral closure.

For voiceless (unaspirated) stops, on the other hand, Stevens states that "the glottis is not actively adjusted from its modal configuration" (p. 323), though he later seems to contradict this statement. The stop closure causes increased intraoral pressure, which will naturally lead to outward displacement of the vocal tract walls

[31] Even with these changes, the reduced transglottal pressure from the stop closure causes both the frequency and the amplitude of the glottal pulses to decrease, sometimes to the point that glottal vibration is not maintained.

and glottis; consequently, the vocal folds to move apart until a short time after the stop is released. In addition, glottal airflow decreases rapidly. Apparently, this passive displacement is not great enough to allow voicing to be maintained, as is the case in the active displacement of the vocal tract walls during voiced obstruents.

However, Stevens also later mentions that, in order to produce a voiceless obstruent, the speaker inhibits vocal fold vibration during the consonant closure by increasing the stiffness of the vocal tract walls and preventing the volume increase that would otherwise naturally occur as a result of increased pressure. Active spreading or constricting of the glottis also serves to inhibit voicing. He suggests that voiceless stops involve "minimal active adjustment" (p. 324).

Löfqvist et al. (1975) assign much greater articulatory effort to voicelessness. In their view, voicelessness is typically brought about through vocal fold abduction, although other aerodynamic factors, such as reduced airflow, may also be necessary to prevent the vocal folds from vibrating. The glottal opening is typically larger for voiceless fricatives than for stops. Glottal abduction requires the suppression of the activity of the interarytenoid, lateral cricoarytenoid, and thyroarytenoid muscles; in addition, the posterior cricoarytenoid muscle is active for voiceless obstruents but not for voiced ones. Tensing the vocal tract also inhibits voicing, as does tightly adducting it. This tight adduction prevents voicing in glottal stops, voiceless implosives, and voiceless ejectives; for these, the thyroarytenoid muscle is responsible. Finally, their experiment shows that the cricothyroid muscle is active for the production of voiceless obstruents; this implies that the increased longitudinal tension of the vocal folds is also used to inhibit voicing. Cricothyroid activity is also correlated with high F0, so this may be a part of the connection between voicelessness and high F0.

However, even if the cricothyroid muscle is not solely responsible, Stevens (1998) states that the fall in F0 following a voiceless consonant may still be accounted for by the fact that the vocal folds are made stiff to maintain the voicelessness of the consonant. When they are relaxed at the release of the consonant, the fundamental frequency drops. Voiceless aspirated consonants are expected to have essentially the same effect on F0 in this regard, except that the glottis is abducted at release of the stop closure in order to produce aspiration. However, like for unaspirated voiceless stops, the increased intraoral pressure from the closure also has the effect of abducting the vocal folds. Stevens suggests that, to counter this pressure, the walls of the glottis (including the vocal folds) are stiffened by the contraction of the cricothyroid and vocalis muscles as well as, possibly, the posterior cricoarytenoid muscle. When the supraglottal constriction is released, then, the pressure drops and the stiffness is allowed to relax. However, at the beginning of the vowel, the greater vocal fold stiffness results in a higher fundamental frequency.

Finally, Maddieson (1997) also suggests that the raising of F0 after a voiceless obstruent may result from the high transglottal airflow occurring when an obstruent is released while the vocal folds are apart; independent evidence shows that increased airflow raises F0. However, as Maddieson points out, this would suggest that voiceless aspirated stops would raise F0 even more than voiceless unaspirated ones; data from Thai show that this is not always the case.

It is likely that these factors work together to contribute to the final result, that high F0 is correlated with voiceless obstruents and low F0 with voiced ones.

3.2.5 Are these the only relevant factors?

The phonetic literature presented in the previous section seems to assume that the connection between voicing and F0 operates below the level of deliberate control. That is, the speaker does not actively manipulate microprosody in any way. Rather, it is simply a side effect of her deliberate consonant articulation. If this is the case, then the connection between consonants and tone is purely articulatory.

However, Honda (2004) also suggests that there may be perceptual motivation for the correlation between voicing and F0: since a listener hears a higher F0 after a voiceless stop, he deliberately raises F0 when he produces a voiceless stop in order to match the auditory cue and enhance the voicing contrast. If this is the case, then the relationship between consonant and tone is not merely intrinsic.

There is certainly evidence that pitch acts as a perceptual cue for voicing. In an experiment by Haggard, Ambler and Callow (1970), English speakers hear a syllable that is ambiguous between /ba/ and /pa/. If the pitch at the beginning of the syllable is falling, it is perceived as /pa/; if it is rising, it is perceived as /ba/. Massaro and Cohen (1976) and Whalen et al. (1993) also provide experimental evidence that low pitch enhances the perception of voicing in English. However, this may simply indicate that the listener has learned the articulatory connection between consonants and tones; speaker awareness does not automatically lead to articulatory enhancement.

There is some evidence that the intrinsic F0 of vowels is partially the result of deliberate manipulation on the part of the speaker (Honda & Fujimura, 1991; Rossi & Autesserre, 1981), though this has been the matter of some debate. The primary evidence for this comes from the fact that the activity of the cricothyroid muscle is positively correlated with vowel height even though this is not anatomically necessary. Thus, researchers conclude that the cricothyroid muscle must be active for pitch control and that the intrinsic changes in F0 resulting from reshaping the vocal tract for different vowels do not fully account for intrinsic vowel F0. If speakers manipulate F0 based on vowel quality in order to enhance an auditory cue, then, it seems plausible that they should do so for consonants as well. However, it would be more difficult to demonstrate since the cricothyroid muscle also serves to maintain voicelessness.

Finally, it has been proposed that the connection between voicing and low F0 is not physiological but rather phonological. Keating (1984) argues that pitch is manipulated as a result of the phonological feature [voice] rather than the phonetic realization of a voiced obstruent. For this reason, pitch is low following phonologically voiced stops in both French and English, despite the fact that these stops have different phonetic realizations. If this is the case, then changes in F0 following a consonant are decidedly under the deliberate control of the speaker rather than purely the phonetic result of voicing control. Kingston and Diehl (1994) argue extensively that this is the case—that realization of the feature [voice] varies considerably across languages but that deliberate changes in F0 following these consonants are one of several reliable cues to this feaure.

It seems clear from all this that there is a natural connection between voicing and low F0 as well as between voicelessness and high F0, even if it is unclear what the precise articulatory basis for this connection is. This pitch difference also enhances the perceptual salience of the voicing distinction (Keyser & Stevens, 2006). When the phonetic coocurrence of voicing and low F0 is assigned phonological significance by a speaker, this translates into a phonological connection between [voice] and low tone. On the other hand, if there is a phonological connection between voicelessness and tone, the prediction based on the phonetics is that [-voice] and high tone should show a natural affinity for one another, while low tone and [-voice] should naturally fail to co-occur.

3.2.6 Other consonant types

The research on the effects of other consonant types on F0 is much less extensive than the research on voicing. However, I include a summary in this section of the information that is known.

3.2.6.1 Glottal and glottalized stops

Glottal and glottalized stops do not seem to have a consistent effect on F0. In Kam, a glottalized coda raises F0 (Edmondson 1992). Presumably, this results from increased tension in the vocal folds. Glottal stops in Arabic have a similar effect (Hombert, 1978). However, Frazier (2008) shows that the F0 of a vowel following a glottalized consonant is lower than that of a voiceless obstruent in Yucatec Maya, though it is higher than that of an implosive or sonorant.

Kingston (2005) points out that glottalized consonants have two different types of articulation. One method of producing glottalization involves an increase in tension resulting from the tight compression of the vocal folds needed to close the glottis, while the other lacks this tight closure and tends to involve creaky phonation. He proposes that the first of these types results in an increased F0, while the second results in a decreased F0 in the following vowel. Although Kingston is specifically concerned with ejectives, this type of reasoning applies to other glottal or glottalized consonants as well; he provides an extensive description of tense and creaky articulation, and points out that there are multiple types of articulations that lead to the same acoustic results.

3.2.6.2 Implosives

Implosives also show variability in their effect on F0, although they seem more likely to be pitch raisers than lowerers. Implosives in Lagwan (Ruff, 2005), for example, are said to have a slight raising effect on pitch. Demolin (1995) indicates that, in Lendu, F0 is high during the prevoicing of voiceless implosives as well as in the following vowel, and that the F0 perturbation caused by voiceless implosives is slightly higher than that caused by voiced implosives. Overall, in Lendu, F0 is highest following a voiceless stop and lowest following a voiced stop, with the implosives falling in between the two.

Odden (2004) states that implosives and voiceless obstruents group together in the Zina dialect of Kotoko as pitch raisers, while voiced obstruents are followed by a lower F0. Odden (2004) also includes references to several additional sources of phonetic data on implosives in Kihehe and Ngiti. Vowels following implosives in Kihehe have a similar onset F0 to those following voiceless consonants, and both of these are higher than F0 following voiced obstruents. Implosives also have a raising effect in Ngiti.

Painter (1978) includes data from Sindhi in his study of consonant types and F0. However, his study does not seem to show consistent patterns across consonant type; for example, at consonant release, the vowels following [p], [gh], and [g] have higher F0 than [dh], which in turn is higher than [d], [m], [bh], [b], and [ɓ]. At 50 ms, this changes to [ɓ], [dh], [g], [gh] > [bh], [m] > [p], [d] > [b]. It seems that either there is no correlation between consonant type and F0 in Sindhi or Painter's methodology is not sufficient to reveal it.

Frazier (2008), on the other hand, shows that both preceding and following implosives have a significant effect on F0 in Yucatec Maya, but that they group with sonorants in producing the lowest F0 value of any of the consonant types—these also include voiceless obstruents, ejectives, and glottalized obstruents. Wright and Shryock's (1993) study of SiSwati also indicates a lower F0 value following implosives than voiceless aspirated obstruents; the F0 value following implosives is higher than the F0 value following nasals for high tone vowels but converges quickly with the nasal values for low tone vowels.

Although this section seems to show a general tendency for implosives to be F0 raisers, these results should be treated with caution, since only Frazier (2008) and Wright and Shryock (1993) provide detailed phonetic analyses including information about statistical significance, and these two studies lack data from voiced obstruents. As will be seen in Chapter 4, the method of measurement can also make a difference in the conclusion that is drawn about microprosodic effects for implosives: implosives raise F0 at vowel onset in Bade, but they lower the overall F0 of the syllable.

The phonetic differences may be due to a difference in articulation, such as the one discussed in the previous section. However, an implosive, unlike an ejective, has potential for F0 lowering and raising even in its canonical form, since it involves both voicing and larynx lowering. On the other hand, Wright and Shryock and Demolin both follow Ohala in pointing out that the pressure drop associated with an implosive greatly increases the airflow at release, which is predicted to lead to increased F0. The increased tension associated with an implosive may also increase F0.

3.2.6.3 Aspiration, voiceless frication, and /h/

Section 3.2.4 briefly discussed the connection between aspiration and F0, citing claims that increased laryngeal tension prior to release should lead to a raising effect after aspirated consonants. In Korean, for example, aspirated onsets are associated with a higher F0 than those of lax onsets (Kim, Beddor, & Horrocks, 2002; Silva, 2006). Pearce (2007) also shows that a longer VOT is correlated with high tone in many dialects of Kera, both in production and in perception.

However, cross-linguistic data suggests that this is not always the case. For example, Xu and Xu (2003) show that aspirated onsets lower F0 in Mandarin, and Francis et al. (2006) show the same for vowel onset F0 in Cantonese. However, Zee (1980) shows the opposite result: that aspirated onsets raise F0 in Cantonese; Francis et. al suggest that this may be the result of a difference in measuring technique. On the other hand, Francis et al. also show that a pitch starting at a higher point acts as a perceptual cue for aspiration in Cantonese—a listener is more likely to perceive an ambiguous onset as aspirated if the beginning of the following pitch is higher; this is the opposite of their expected result.

Hombert (1978) contrasts the effects on F0 of glottal stop and [h] in Arabic, and demonstrates that [h] has a lowering effect. However, his survey of the literature also shows cross-linguistic variability with respect to [spread glottis].

Downing and Gick (2001) suggest that variability of this sort is expected, arguing that, in the production of aspiration, “distinct mechanisms are employed across different languages, and even different speakers of the same language, for producing aspiration/frication, and that these production mechanisms affect the F0 of following vowels in distinct ways, which in turn may become phonologized in some tone systems”(7). They cite as evidence Erickson et al’s study of Thai in which 8 of 11 subjects have higher F0 onset values following voiceless aspirated stops than voiceless unaspirated stops, but the other three speakers show the opposite pattern. They also cite Cohn and Lockwood (1994)’s study on Madurese, which shows that voiceless aspirated onsets lower the following F0 significantly and are longer in duration than voiced or voiceless unaspirated stops.

Downing and Gick offer the Madurese data as support for their own study, which shows that the depressor fricatives in Nambya and the depressor voiceless aspirated stops in Botswana Kalanga'a differ from the non-depressor variants of these sounds in their duration; a longer period of frication is phonologically associated with low tone in these languages. This corresponds to McCrea and Morris' (2005) results from English, where they find that the duration of aspiration is significantly shorter in an utterance pronounced with high F0 than it is for one pronounced with low F0.

Silva (1998) reasons that the increased airflow for [spread glottis] increases the rate of vibration of the vocal folds, while Stevens (1998) points to increased stiffness in the vocal tract as the source of raised F0 following aspiration. However, although Downing and Gick (2001) suggest that multiple production types lead to the difference in F0 effect, they do not indicate what these production types might be. One possibility is that a lower air pressure leads to an F0 drop.

It should also be noted that, although these sounds share some acoustic properties and have similar effects on tone, this does not mean that fricatives have the same feature specification as aspirated stops. In Kam, for example, voiceless fricatives do not interact with tone. However, Vaux (1998) proposes, based on evidence from a number of languages, that voiceless fricatives have the default feature specification [+spread glottis]; if this is the case, then their patterning with aspirated consonants is predicted.

3.2.6.4 Other consonant types

An even smaller amount of research exists for other consonant types. Low F0 is the biggest perceptual cue for lax onsets in Korean, and F0 plays a role in perception of tense and aspirated onsets as well (Kim, Beddor, & Horrocks, 2002; Silva, 2006)

Ikwere (Clements & Osu, 2002) contrasts a voiced obstruent, a voiced pressureless obstruent, and a voiceless ingressive obstruent. Of these, F0 following the voiced obstruent is lower than the other two, which are quite similar to each other.

Also, as previously mentioned, Frazier (2008) includes data on ejectives; in Yucatec Maya the F0 following these sounds is higher than that following a glottalized segment, an implosive, or a sonorant, but lower than the F0 following a voiceless obstruent.

3.3 Bade

Having established a phonetic and phonological basis for consonant-tone interaction, I now examine how it plays out in Western Bade, a language previously unaddressed in the OT literature. In this language, voiced obstruents block high tone spreading, while voiceless obstruents block low tone spreading; sonorants and implosives are not tone blockers. The interactions follow from constraints against specific values of [voice] co-occurring with specific tone values: [+voice] cannot occur within a high tone span, while [-voice] cannot occur within a low tone span. This section illustrates these constraints by providing an Optimality Theory analysis of tone spreading in Bade. Finally, voice-tone interaction is placed in the larger context of voicing in Bade, and it is argued that the data can only be explained by using an binary [voice] feature and by representing voicing and tone by independent features.

Bradshaw (1999) briefly addresses these data. However, she includes only the high tone spreading data and makes no mention of implosives.

3.3.1 Data

The Bade language has previously received scant attention in the literature; the tone facts are addressed in Schuh (1978) and incorporated into Bradshaw's (1999) survey. The data in this paper are taken from an unpublished manuscript (Schuh, 2002) and a dictionary (Dagona, 2004). In this paper, I specifically address the Western dialect of the language; tone facts differ in the Gashua dialect.

Bade has two tones, high (H) and low (L). Falling tones are also permitted on certain heavy syllables, and, very rarely, rising tones occur. In general, tone is lexically and phonologically determined. However, the tones of verbs are morphologically determined; for example, the verb 'release' is *tàɗú* with a low-high tone pattern in the completive, but *táɗì* with a high-low tone pattern in the subjunctive.

In Bade, a voiced and voiceless series of stops and fricatives contrast with one another. In addition, these contrast with a series of implosives at three places of articulation. The full consonant inventory is provided in Table 4.

	Labial	Alveolar	Palatal	Lateral	Velar		Glottal	
Voiceless stop	p	t	tʃ		k	kʷ		
Voiced stop	b	d	dʒ		g	gʷ		
Implosive	ɓ	ɗ	ɗʲ					
Voiceless fricative	f	s	ʃ	ɬ			h	hʷ
Voiced fricative	v	z	ʒ	ɮ			ɦ	ɦʷ
Nasal	m	n	ɲ		(ŋ)			
Liquid		r		l				
Glide			j			w		

Table 4. Bade consonant inventory

Tones and consonants interact with one another in Bade; specifically, non-implosive voiced obstruents block high tone spreading, while voiceless obstruents block low tone spreading.

3.3.2 High tone spreading

I first address the facts regarding high tone spreading. While the exact prosodic/syntactic domain of high tone spreading is unknown, it is clear that, in the typical case, the high tone spreads rightward across word boundaries. (17) below shows three verbs in their citation form; examples of high tone spreading are provided in (18), where the high tone from the pronoun *nə́* spreads to the following verb, and in (18d), from the verb to the direct object. This spreading applies iteratively, as is seen in each of the examples provided in (18).

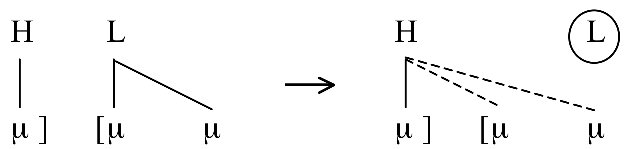
17. Completive verbs
    a. tə̀nkə̀kú 'pressed'[32]
    b. ɗùwàɬú 'became tired'
    c. mə̀skə̀tú 'turned'

[32] The completive has a LH tone pattern.

18. High tone spreading
    a. /nə́ tə̀nkə̀kú/ > nə́ tə́nkə́kú 'I pressed'
    b. /nə́ ɗùwàɬú/ > nə́ ɗúwáɬú 'I got tired'
    c. /nə́ mə̀skə̀tú/ > nə́ mə́skə́tú 'I turned'
    d. /nə́ mə̀skə̀tú kùnàfə́n/ > nə́ mə́skə́tú kúnáfə́n 'I turned an adze'

Some variability exists regarding the pronunciation of the final vowel in the words that have undergone spreading. Though the status of downstep in Bade remains somewhat unclear (Schuh, 2002, in press), the final syllable of the verbs in (18) is downstepped, at least for some speakers. This implies that, when the high tone spreads, the spreading high tone does not actually overwrite the tones of the following word. Instead, the low tone becomes a floating tone and the final high tone retains its position. Here, I make the simplifying assumption that this is representationally true for all speakers but that the floating low tone is only optionally realized phonetically as downstep. Thus, high tone spreading can be represented schematically as follows:

19. High tone spreading



High tone spreading does not apply whenever there is a high-low tone sequence, however, as indicated by the surface high-low sequences exhibited by the words in (20):

20. Evidence against word-internal high tone spreading[33]
    a. sú:lîyà 'worthless'
    b. kó:lò:rîyón 'type of fish'
    c. lá:kì 'small'
    d. wúnyà:nyà 'someone's daughter' (reduplicated from wúnyán)
    e. də̀káúyà 'fried' (də 'stative' + káúy 'fry' + à 'stative')[34]

[33] Examples like these are relatively rare, suggesting that high tone spreading has had some influence, whether historical or synchronic, in shaping the lexicon.

The first three examples in (20) show that high tone spreading does not apply within a morpheme. Moreover, while the effects of different types of boundaries on tone spreading have not been fully studied in Bade, (20d) and (20e) show that high tone spreading also fails to occur across at least some word-internal morpheme boundaries. However, this is likely phonologically rather than morphologically driven since high tone generally fails to spread to the final syllable of a word, in effect disallowing a floating tone to occur at a word boundary.

However, the data in (18) make it clear that the boundary between the clitic *nə́* and the verb, as well as between the verb and its direct object, both trigger spreading. Nevertheless, even in environments where high tone typically spreads, the spreading is blocked by a phonologically voiced obstruent, as shown in (21) (cf. (18)).

21. High tone spreading blocked by a voiced obstruent
    a. /nə́ tə̀mbə̀lú/ > nə́ tə́m**b**ə̀lú 'I pushed'
    b. /nə́ bàzàrtú/ > nə́ **b**àzàrtú 'I shamed'
    c. /nə́ mə̀skə̀tə́ gàpàtʃə́mə́n/ > nə́ mə́skə́tə́ gàpàtʃə́mə́n 'I turned a beam'
    d. /nə́ tə̀nkə̀kú gàngán/ > nə́ tə́nkə́kú gàngán 'I pressed a drum'

These examples also show that only non-implosive voiced obstruents block high tone spreading; (18a) provided an example of a high tone spreading across the voiceless obstruent [t], (18b) of a high tone spreading across the phonetically voiced implosive [ɗ], and (18c) of a high tone spreading across the phonetically voiced nasal [m].

3.3.3 Low Tone Spreading

Low tones also spread rightward in Bade, but spreading and blocking are both different from the high tone patterns previously discussed. A low tone spreads to a

[34] *də-* is assigned a tone opposite that of the stem. Verbs are assigned tone based on tense, aspect, and modality (TAM); in this case, the stem is given high tone. In many cases the verb stem tone assignment is influenced by consonant type, though I do not address this here. See Schuh (2007) for details about morphological processes.

following high-toned syllable across a clitic boundary or within the same morpheme, as seen in (22). Thus, currently available data suggest that the domain of low tone spreading is the phonological word.

22. Low tone spreading
    a. /dʒə̀.ɗgə́ kó:rón/ > dʒə̀.ɗgə̀ kó:rón 'we followed a donkey'
    b. /dʒə̀ kə̀rə́ kó:rón/ > dʒə̀ kə̀rə̀ kó:rón 'we stole a donkey'
    c. /dʒə̀ tàɗə́ kó:rón/ > dʒə̀ tàɗə̀ kó:rón 'we released a donkey'
    d. /kàyá:n pə́m/ > kàyà:n pə́m 'not a squirrel'

Low tone spreading only occurs, however, if the target syllable precedes another high tone, as is the case for the verbs preceding *kó:rón* 'donkey' in (22) and the noun preceding *pə́m* 'not'. If a low-initial noun is substituted, as shown in (23), no spreading occurs.

23. No spreading preceding another low tone
    /dʒə̀.ɗgə́ dùwún/ > dʒə̀ɗgə́ dùwún 'we followed a horse'

In particular, this means that low tone spreads at most one syllable within a word; if the word is longer than two syllables, low tone fails to spread, as in (24).

24. a. gə̀ráwán hé:tá 'white gourd bottle'
    b. màɗálmán gá:gárè 'big repairman'

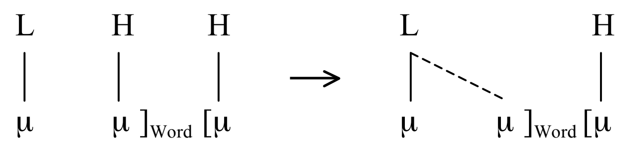
Although low tone spreads within a word, there must be a word boundary before the triggering high tone, since the low tone does not spread in the words in (25), whether morphologically simple or complex, despite the fact that, in each of them, a low tone precedes two high tones.

25. Evidence against internally triggered low tone spreading
    a. bàrbî:rámə́n ‘large pot’
    b. ǹgárákún ‘shield’
    c. gànáwá ‘ripe’(= ga ‘stative’ + náw ‘ripen’ + á ‘stative’)[35]
    d. gàrápáɗá ‘boiled’ (= ga ‘stative’ + rápáɗ ‘boil’ + á ‘stative’)
    e. màrá:kə́ná:n ‘traveler’ (= ma ‘agentive’ + rákə́n ‘travel’ + á:n ‘agentive’)

Bade does not have an appropriate morphological environment to determine whether a low tone could spread to a final syllable and then spread over a boundary if that syllable were also in the correct phonological environment: LH#H#H is not known to be possible in the language (Schuh, p.c.).

Low tone spreading, then, can be represented schematically as follows.

26. Low tone spreading



In some sense, then, low tone spreading has the opposite effect of high tone spreading; while high tone spreading typically crosses over word boundaries, low tone spreads up to a word boundary.

Whereas high tone spreading is blocked by voiced obstruents, low tone spreading is blocked by voiceless obstruents, as shown in (27) (cf. (22)).

27. Low tone spreading blocked by a voiceless obstruent
    a. /dʒə̀ də̀psə́ kó:rón/ > dʒə̀ də̀**ps**ə́ kó:rón ‘we hid a donkey’
    b. /dʒə̀ gàfá kó:rón/ > dʒə̀ gà**f**á kó:rón ‘we caught a donkey’
    c. /tə̀rká:n pə́m/ > tə̀r**k**á:n pə́m ‘not an orphan’
    d. /mə̀tə́n pə́m/ > mə̀**t**ə́n pə́m ‘not death’

Attributing this blocking effect to a phonological [-voice] highlights the parallel nature of high tone spreading and low tone spreading. Furthermore, it would be problematic

[35] *ga- -á* derives participial adjectives from intransitive verbs, while *də- à* 20 derives resultative statives from transitive verbs. Tone assignment for the prefix and stem is the same for both types of statives, as well as for agentives formed by *ma- -á:n*.

to attribute the blocking to a consonant that is unspecified for [voice], since neither sonorants nor implosives block low tone spreading, as seen in (22b) and (22c) respectively. In (22b), the low tone spreads over the sonorant [r], and in (22c) it spreads over the implosive [ɗ]. Since the existence of [-voice] is somewhat controversial (see Wetzels and Mascaró (2001) for a summary), and since it has specifically been claimed that voiceless obstruents do not interact with tone (Bradshaw, 1999), I address this claim more carefully in the remainder of this subsection.

3.3.4 Consonant-tone sequences

The restrictions on spreading illustrated above do not apply to underived consonant-tone sequences. The data in (28) below show that, although a high tone cannot spread across a voiced obstruent, it can follow one. Similarly, the data in (28) show that a low tone can follow a voiceless obstruent even though it cannot spread across one.

28.	a. kà**bí**:n	‘type of mat’	**gá**vgàɗá	‘rotten’
	dʒápà	‘small (amount)’	**bú**:zərá:n	‘cracked soil’
	b. **pə̀**mán	‘type of measure’	lá:**kì**:	‘small’
	ɬə̀mə́n	‘chin’	á:m**fə̀**ɗá:n	‘headstrong person’

Bade also permits underlying sequences that otherwise parallel the hypothetical results of disallowed spreading. (29a) gives examples of sequences of a high tone followed by a voiced obstruent followed by another high tone; tone spreading cannot result in such configurations since the voiced obstruent blocks spreading. (29b) provides parallel examples of sequences of a low tone followed by a voiceless obstruent and another low tone.

29.

a.	ánk**ábá**n	‘sorghum’	b**ə́rgó**n	‘waterbuck’
	kár**ágá**n	‘forest’	g**á:gá**rè	‘big’
b.	**əɬkʷà**mə́n	‘weaver’	d**ùksà**:kwén	‘weight’
	m**à:pì:**ɗán	‘long straw’	g**àtà**vén	‘type of senna plant’[36]

3.3.5 Constraints

Thus far, I have outlined the high and low tone spreading patterns in Bade and have shown that high tone spreading is blocked by non-implosive voiced obstruents while low tone spreading is blocked by voiceless obstruents. I now show that these data can be accounted for using constraints that ban specific laryngeal features from occurring within a tone span. However, the tone span is defined in such a way that the data in (28) and (29) are still permitted to surface because, in Bade, the syllable onset is, by default, excluded from a monosyllabic span.

The constraints used for Bade rely on the notion of tone span in that [-voice] cannot occur within the span of a low tone and [+voice] cannot occur within the span of a high tone.

30. L→¬[-vce]: Incurs one violation for each [-voice] feature associated to a segment in a low tone span.

31. H→¬[+vce]: Incurs one violation for each [+voice] feature associated to a segment in a high tone span (cf. Cassimjee, 1998).

Inherent in these constraints is the assumption that ¬[-vce] is not equivalent to [+vce]; this will be discussed at some length in Section 3.3.8. I also use these constraints instead of [+vce]→L “if [+voice] then low” and [-vce]→H since there is no evidence that every consonant with a voice specification in Bade is contained in a tone span. Though higher ranked constraints could prevent consonant-only tone spans, the analysis is much clearer using the constraints in (30) and (31).

[36] As a reviewer points out, it would be helpful to know what happens to these words in a high tone spreading environment. However, these data are not available. The analysis presented here predicts that the tone would spread only to the first syllable of those that do not begin with a voiced obstruent. Verbs behave differently since they do not have preassociated tone patterns.

In addition, the following constraints are used in this discussion:

32. ALIGN(H,Rt): Incurs one violation per mora for each high tone that is not aligned to the right edge of the phrase.[37]

33. ALIGN(L,Rt): Incurs one violation per mora for each low tone that is not aligned to the right edge of the phrase.

34. MAXT: Incurs one violation for each input tone that has no correspondent in the output.

35. DEPT: Incurs one violation for each output tone that has no correspondent in the input (cf. McCarthy and Prince, 1994).

36. IDENT[voi]: Incurs one violation for a change of [+voi] to [-voi] or vice versa.

37. OCP(H): Incurs one violation for a pair of high tone spans with no low tone span between them (cf. McCarthy & Prince, 1994; Myers, 1997).

38. SPAN⊇MORA: A span does not have a mora-internal boundary (cf. ONE-T/μ (Yip, 2002), *[TT]μ (Morén & Zsiga, 2006)).

39. *DISPLACE: Incurs one violation for each non-floating output tone whose span does not include the mora(s) corresponding to that tone in the input (cf. INCORPORATE F-SPONSOR (Cassimjee & Kisseberth, 1998)).

40. MAXSPAN: Incurs one violation for each tone span that is present in the input but not in the output.

41. *H#L: Incurs one violation for a low tone that follows a high tone across an intervening word boundary.

While the majority of these constraints are common in the literature,*DISPLACE benefits from a more formal definition as follows.

[37] While there are clear problems with the predictions of gradient constraints (McCarthy 2004), the mechanism of alignment is tangential to the issue of consonant-tone interaction; thus Align is used for the sake of its familiarity. Segment-based alignment and mora-based alignment are equally applicable to the data presented in this section, but violations of alignment constraints are assigned the more familiar moraic counts. When I refer to a segment being contained in a span, it means that the mora to which that segment is associated is contained in the span.

42. Let *t* and *m* be in the input and *t'* and *m'* in the output, and let *t* and *t'* be tones and *m* and *m'* be moras. If *t* corresponds to *t'*, and *m* to *m'*, and if there are two spans *s* and *s'* such that *s* is the span for *t* and *s'* is the span for *t'*, then if *m* is in *s, m'* is in *s'*.

That is, for all output moras that have corresponding input moras, each mora included in an input tone span must also be included in the corresponding output tone span. This is similar to the IDENT family of constraints, in that a span in the input must have a corresponding span in the output in order for a violation to occur. Consequently, no violations are incurred if either the input or the output tone is floating since floating tones have no corresponding spans.

In the tableaux presented here, the representations given in the inputs make several assumptions about the nature of tone association in Bade. Lexically determined tones, such as those of nouns, are assumed to be associated with TBUs in the input. On the other hand, since the surface pattern of the morphologically determined verbal tone patterns is derivable, these are regarded as floating tones in the input. Floating tones are designated by a capital L or H, while docked tones are represented indirectly through the location of the span with which they are realized. Spaces in inputs represent a word boundary. This discussion abstracts away from issues of vowel elision, and richness of the base issues are not dealt with systematically.

3.3.6 Spreading and blocking

High tone spreading in Bade is accomplished by the combined effects of two constraints, *H#L and ALIGN(H,Rt). Since *H#L is violated by a high tone at the right edge of a word, the violation can be alleviated through the rightward spreading of this tone. However, this constraint alone will not induce iterative spreading; a second constraint such as ALIGN(H,Rt) is still needed. The phrase evaluated in the tableau below is repeated from (18); the morphological LH tones are represented as floating in the input. As previously indicated, I count alignment violations by mora, resulting in only three violations for the five segments intervening between the first high tone and the right edge of the phrase in (d).

43.

	n[ə]$_H$ LH ɗuwaɬu	MAXT	*H#L	ALIGN(H,Rt)
a.	☞ n[ə ɗuwa]$_H$ L ɬ[u]$_H$			*
b.	n[ə ɗuwaɬu]$_H$	*!*		
c.	n[ə ɗu]$_H$ w[a]$_L$ ɬ[u]$_H$			**!
d.	n[ə]$_H$ ɗ[uwa]$_L$ ɬ[u]$_H$		*!	***

Here, candidate (d) loses because of the high-low sequence over a word boundary, while candidate (c) loses because the initial high tone is not aligned as fully as possible to the right edge of the phrase. Candidate (b), where the high tone is fully aligned to the right, loses because it violates the higher ranked MAXT. Thus, candidate (a) is optimal when MAXT >> ALIGN(H,Rt) since all input tones are still present and only one violation of ALIGN is incurred.[38]

The issue of rightward spreading over nouns is slightly more complex since nouns have preassociated input tone. In a second phrase repeated from 18, /nə́ məskətú kùnàfə́n/, where *kùnàfə́n* 'adze' has fully specified input tone, spreading still occurs, but the additional constraint *DISPLACE is needed to prevent partial spreading. The following tableau omits the portion *nə́ məskə-* for the sake of simplicity.

[38] In this and subsequent tableaux, there are possible candidates that violate neither ALIGN nor MAX, such as n[ə ɗuwaɬu]$_H$LH, with two floating tones at the end. Since there is no evidence for such forms surfacing in Bade, it is assumed that constraints ban outputs with structures such as multiple floating tones or floating high tones, and these forms are not further discussed.

44.

… $t[u]_H$ $k[una]_L f[ən]_H$	*DISPLACE	MAXT	*H#L	ALIGN(H,Rt)
a. …$t[u]_H k[una]_L f[ən]_H$			*!	****
b. ☞ …$t[u\ kuna]_H$ L $f[ən]_H$				**
c. …$t[u\ kunafən]_H$		*!*		
d. …$t[u\ ku]_H n[a]_L f[ən]_H$	*!			***

Candidate (a), the fully faithful candidate, is eliminated here due to the high-low tone transition at a word boundary. Candidate (c) fails because two tones are deleted. Candidate (d) maintains all its input tones and alleviates the boundary issue; however, it violates *DISPLACE since the input low tone span is [una], but [un] is omitted from the low tone span in the output. Consequently, candidate (b) is chosen as the output form; it does not violate *DISPLACE because the floating low tone has no span and therefore no corresponding span in the input, so the conditions for *DISPLACE are not met. This shows, then, that *DISPLACE must also be ranked above ALIGN(H,Rt).

However, when a voiced obstruent is present, such as the [b] in (45), high spreading is blocked. I assume, when counting violations, that sonorants are unspecified for [voice].

45.

$n[ə]_H$ LH təmbəlu	H→¬[+vce]	IDENT[voi]	ALIGN(H,Rt)
a. $n[ə\ təmbə]_H$ L $l[u]_H$	*!		*
b. ☞ $n[ə\ təm]_H\ b[ə]_L\ l[u]_H$			**
c. $n[ə\ təmpə]_H$ L $l[u]_H$		*!	*

Thus, candidate (a), which is otherwise parallel to candidate (a) in (43), is eliminated by the constraint H→¬[+vce]. The violation occurs because the [b] is located within the span of the high tone. In the optimal candidate (b), no such violation occurs; since H→¬[+vce] >> ALIGN(H,Rt), this candidate wins. Candidate (c) represents the fact that H→¬[+vce] cannot be repaired via a change in voicing in Bade; thus, voicing faithfulness must also be ranked above ALIGN(H,Rt).

Low tone spreading and blocking work in a way that is analogous to the high tone spreading already presented. Thus, low tone spreading is generally driven by the constraint ALIGN(L,Rt). Here, CV:N syllables are counted as bimoraic. *DISPLACE is not included in the tableau since none of the candidates violate it; all output tone spans have a domain that is the same or larger than their corresponding input tone spans.

46.

	$k[a]_L y[a{:}n]_H\ p[\text{ə}m]_H$	OCP(H)	MAXT	ALIGN(L,Rt)
a.	☞ $k[aya{:}n]_L\ p[\text{ə}m]_H$		*	**
b.	$k[a]_L\ y[a{:}n]_H\ p[\text{ə}m]_H$	*!		****
c.	$k[a]_L\ y[a{:}n\ p\text{ə}m]_H$		*	***!*

The fully faithful candidate in (b) loses due to an Obligatory Contour Principle violation, showing that OCP(H) must be ranked above MAXT. As mentioned in section 3.3.3, low spreading occurs only in the presence of a high tone in a following word. Richness of the base issues aside, it is the concatenation of two words that will bring about two adjacent high tones, thus incurring the violation that results in spreading. In principle, this violation might be alleviated either through collapsing the high tones or through rightward spreading of the low tone. However, collapsing the two high tones does not reduce the number of alignment violations for the low tone. As a result, candidate (a) harmonically bounds candidate (c) under all constraints considered in this analysis; thus, (a), with rightward spreading of the low tone, wins.

Blocking by a voiceless obstruent is achieved, then, by ranking L→¬[-vce] above ALIGN(L,Rt).

47.

$m[ə]_L t[ən]_H\ p[əm]_H$	L→¬[-vce]	OCP(H)	DEPT	MAXT	ALIGN(L,Rt)
a. $m[ətən]_L\ p[əm]_H$	*!			*	**
b. $m[ə]_L\ t[ən]_H\ p[əm]_H$		*!			****
c. ☞ $m[ə]_L\ t[ən\ pəm]_H$				*	****
d. $m[ə]_L\ t[ən]_H$ L $p[əm]_H$			*!		****

Here, candidate (a) is eliminated by L→¬[-vce], since the voiceless [t] is within the span of the low tone. The insertion of a floating tone as an OCP alleviation, as in candidate (d), is also not permitted due to the high ranking of DEPT. Thus, candidate (c), where the OCP violation of the fully faithful candidate in (b) is alleviated through the collapse of the two H tones, is permitted to surface.

The basic constraint ranking necessary for achieving voice-tone interaction in Bade, then, is as follows:

48. H→¬[+vce], L→¬[-vce][39], OCP(H), IDENT[voi] >> *DISPLACE, MAXT, *H#L[40] >> ALIGN(H,Rt), ALIGN(L,Rt)

This ranking also prevents tone spreading within words. I illustrate this word-internal faithfulness with the word *sú:lìyà* 'worthless', in which the high tone fails to spread despite an apparently optimal environment for spreading—there are no voiced obstruents in its path. The candidates considered here assume that Bade obeys the classic OCP constraints on tone (see Odden, 1986).

49.

$s[u]_H l[iya]_L$	*DISPLACE	MAXT	ALIGN(H,Rt)
a. ☞ $s[u]_H l[iya]_L$			**
b. $s[uli]_H y[a]_L$	*!*		*
c. $s[uliya]_H$		*!	

In (49), the fully faithful candidate, (a), surfaces because, although ALIGN is active in Bade, it is ranked low. Candidate (c) shows that the high tone cannot spread

[39] On the basis of these data, *L/[-vce] cannot be ranked with respect to *DISPLACE and MAXT, but it must be ranked above ALIGN(L,Rt).
[40] The position of this constraint will be argued for in section 3.2.

throughout the word because the higher ranked MaxT prevents the deletion of the low tone. In candidate (b) where the low tone surfaces on only one syllable, high tone cannot spread because, in doing so, it displaces the low tone; the low tone is attached to [i] in the input, but the [i] is not included in its span in the output.

3.3.7 Falling tone

The blocking of spreading is not the only way consonants affect tones in Bade. Lexical falling tone is permitted only on bimoraic syllables (see Zhang, 2001), but it does not occur on syllables that are closed with a voiceless obstruent. Thus, in 50, the falling tones are legal because they occur on heavy syllables; the syllable may be heavy due to a coda consonant, whether sonorant or obstruent, or due to a long vowel.

50.	a. ɗûgdán	'lame person'	mâŋgán	'friend'
	ɬâːwán	'rake'	áùnàkón	'custard apple'
	b.*dûdán		*mâgá	
	c.*dûktú		*mâfká	

The forms in (b), however, are impossible words in Bade since the falling tone occurs on a light syllable. Words like those in (c) are also not permitted; although voiceless codas presumably create heavy syllables in Bade, falling tone cannot occur on these syllables.

Of the actual words given in (50), *áùnàkón* presents the greatest difficulty.[41] For this word to surface faithfully, the constraint MAXSPAN must also be used.

[41] Schuh (p.c.) indicates that this word may be derived from *ágùnàkón;* if so, this may remove the difficulty, but the same principles apply to other words with falling tone.

51.

[a]$_H$[una]$_L$k[on]$_H$	*Displace	MaxSpan	MaxT	Align(H,Rt)
a. ☞ [a]$_H$[una]$_L$k[on]$_H$				****
b. [auna]$_H$ L k[on]$_H$		*!		**
c. [aunakon]$_H$		*!*	**	
d. [au]$_H$n[a]$_L$k[on]$_H$	*!*			***

Here, the floating low tone in candidate (b) violates MaxSpan since there is no output span corresponding to the low tone span in the input. The fully aligned high tone in (c) violates MaxT and MaxSpan, and the adjustment of the low tone span in (d) violates *Displace. Consequently, the fully faithful candidate in (a) surfaces.

The addition of the constraint MaxSpan presents a potential problem for high tone spreading since a span may be deleted in order for tone to spread. In order to avoid such problems, MaxSpan must be ranked below *Displace and *H#L. This is illustrated by the tableau below, repeated from (44) above with MaxSpan added.

52.

… t[u]$_H$ k[una]$_L$f[ən]$_H$	*Displace	MaxT	*H#L	MaxSpan	Align(H,Rt)
a. …t[u]$_H$k[una]$_L$f[ən]$_H$			*!		****
b. ☞ …t[u kuna]$_H$ L f[ən]$_H$				*	**
c. …t[u kunafən]$_H$		*!*		**	
d. …t[u ku]$_H$n[a]$_L$f[ən]$_H$	*!*				***

Because MaxSpan is ranked lower than these three constraints, there is no change in the selection of the winning candidate. The crucial role of *H#L with regard to high tone spreading can now be seen; it is this constraint that rules out the fully faithful candidate. Ranking this constraint above MaxSpan ensures that spreading happens across word boundaries even though it does not occur within a word.

The new constraint ranking, then, is as follows:

H→¬[+vce] Ident[voi] *H#L *Displace DepT OCP(H) L→¬[-vce]

MAXSPAN MAXT ALIGN(L,Rt)

ALIGN(H,Rt)

Figure 4. Bade Constraint Ranking[42]

This can now be tested, with the addition of the never-violated constraint SPAN⊇MORA, against an input with falling tone on a syllable closed in a voiceless obstruent, like **dûktú*, that cannot surface.

53.

	d[u]$_H$[k]$_L$t[u]$_H$	SPAN⊇MORA	*DISPLACE	L→ ¬[-vce]	MAX T	ALIGN (H,Rt)
a.	d[u]$_H$[k]$_L$t[u]$_H$			*!		**
b.	d[u]$_H$k L t[u]$_H$					*!*
c.	☞ d[uk]$_H$ L t[u]$_H$					*
d.	d[u]$_{HL}$ k.t[u]$_H$	*!	*			**
e.	d[uktu]$_H$				*!*	
f.	d[uk]$_H$ t[u]$_L$		*!		*	*

The prediction is that candidate (c), *dúktú* (with potential downstep) will surface, and more importantly, that the fully faithful candidate (a) will not. Candidate (e) fails for MaxT violations, as we have seen before. However, the other candidates are more interesting. Candidate (a), while theoretically possible, is ruled out because the low tone span includes the voiceless [k], thus violating L→¬[-vce]. One possible repair, found in (d), is to contract the falling tone so that it only occurs on one mora of the syllable. However, Bade does not permit a contour tone on a monomoraic syllable, so this candidate is ruled out by SPAN⊇MORA; moreover, the fact that [k] is no longer contained in the low tone span causes this candidate to violate *DISPLACE. A third possibility, found in (b), is to simply remove the [k] from a span and allow the low

[42] This ranking has been checked in the context of a larger set of data, candidates, and constraints using OTSoft (Hayes et al., 2003).

tone to float. However, here ALIGN(H,Rt) is violated twice, since the moraic [k] is still a violation even if it carries no tone. Finally, candidate (e), where the high and low tones have been reassigned, is ruled out because the second high tone is deleted, violating MAXT. Consequently, the preferred output places both [uk] and [u] in high tone spans, with the low tone left floating.

Finally, this basic ranking, with the addition of IDENT[voi], H→¬[+vce] >> OCP(H), DEPT, *DISPLACE, predicts that a word like [kárágán] 'forest' will surface with two tone spans, even if only one span is present in the input. Since these constraints were all previously undominated, the previous results will still obtain. I provide a tableau for the input k[aragan]$_H$ in (54), and consider only outputs with high tones.

54.

k[aragan]$_H$	IDENT[voi]	H→¬[+vce]	*DISPLACE	DEPT	OCP(H)
a. k[aragan]$_H$		*!			
b. ☞ k[ara]$_H$g[an]$_H$			*	*	*
c. k[a]$_H$r[a]$_H$g[an]$_H$			*	*!*	**
d. k[arakan]$_H$	*!				

The faithful input in (a) loses here because the voiced [g] causes it to violate H→¬[+vce]. However, this violation cannot be alleviated by devoicing the [g], as in candidate (d), because this now violates IDENT[voi]. The optimal output in (b) violates *DISPLACE, DEPT, and OCP(H); however it violates them less than output (c) does. Consequently, the winning candidate surfaces with two tone spans, omitting the voiced [g] from a span.

3.3.8 Implications for features

Voicing interacts with tone in Bade, but there are also independent constraints on [voice] in Bade. This section examines the distribution of voiced and voiceless obstruents, as reported by Schuh (2002), in order to show that the view of voicing assumed in the previous section is consistent with the overall picture of voicing in the language. In particular, I address here the idea of binary voicing and consider whether it would be possible to account for the Bade data using only privative voice. Under appropriate constraint definitions, the voicing data on their own are consistent with either a binary or a privative voicing view; in tone research, the latter is espoused by Bradshaw (1999) and Hermans and van Oostendorp (2000). However, I argue that only a binary voicing analysis is able to account for both the voicing data and the tone data; the fact that sonorants and implosives do not block tone spreading will prove crucial for this argument.

3.3.8.1 Voicing in Bade

Word-final obstruents are rare in Bade since nouns end either in *–n*, due to the historical process of nunation, or in a vowel in the definite form, and all finite verbs end in a vowel. However, borrowed words and ideophones do occasionally end in obstruents, and these obstruents are voiceless, as shown in (55).[43]

55. Word-final voicing prohibited

mə̀ná:fə̀**k**	'evil'	*mə̀ná:fə̀g
də́ŋgúrú**f**	"the tale is over"	*də́ŋgúrúv

Word-final devoicing is consistent with both hypotheses; either the feature [voice] or the feature [+voice] is blocked from word-final position. Likewise, the fact that syllable-final stops and fricatives agree in voicing with the onset of the following syllable, as demonstrated in (56), is inconclusive.

[43] In the closely related Gashua dialect, nunation has not taken place, and this dialect shows word-final devoicing.

56. Voicing agreement in syllable codas

a. dʒə**pk**ú	'to complete'	dʒà:**pɬ**án	'etchings'
gà**ft**á:n	'side'	ə**sf**án	'sweep, rake'
*dʒə**bk**ú		*dʒà:**pɮ**án	
b. ɗə**bd**ú	'to sell'	tú**gʷz**àrá:n	'sorcerer'
sà**zv**ú	'pour from calabash'	fà**vd**ú	'hit repeatedly'
*sà**sv**ú		*fà**vt**ú	

These examples show that, while obstruents frequently occur in coda position, a voiced coda never precedes a voiceless onset, and likewise, a voiceless coda never precedes a voiced onset.

However, a syllable-final sonorant or implosive need not agree in phonetic voicing with the onset of the following syllable, as shown in (57). The examples in (57a) demonstrate that a phonetically voiced implosive can precede either voiceless [p] or voiced [b]; likewise, the words in (57b) show that a sonorant can precede either voiceless [k] or voiced [g].

57. Implosives and sonorants in coda position

a. hʷì:**ɗp**á:n	'whip'	hà**ɗb**ú	'admonish'
b. zə̀**rk**á:n	'stream'	bə̀**rg**ón	'cleverness'

Coda obstruents are generally not permitted before a sonorant or implosive onset.[44]

The binary voicing hypothesis, then, provides a more straightforward analysis of these data. In this view, all obstruents with contrastive voicing are specified [±voice], while sonorants and implosives are underspecified for the feature [voice][45].

[44] Two phonologically voiced obstruents occur in coda position before a sonorant or implosive: /g/ and /gʷ/. However, velar stops are frequently, perhaps always, lenited in this position (Schuh, p.c.). Thus, it is likely that they do not require a voicing specification in the coda position. If they do, then these data are somewhat problematic for either view—the coda [g] itself is not a problem but rather the fact that no other coda obstruents occur. If a phonologically voiced obstruent can occur in this position, it would require that the voicing faithfulness constraints be divided according to syllable position and place of articulation, with faithfulness to velar coda obstruents being ranked higher than faithfulness to other coda obstruents.

[45] This could also be construed as an argument for ternary [voice] (Noske 1995) or a division of voicing into two features such as [vocal fold vibration] and [pharyngeal expansion].

Adjacent specified [voice] features must agree, and Bade has word-final, rather than syllable-final, devoicing. Underspecification persists throughout the phonological component, but the phonetics are able to fill in the default phonetic voicing values since voicing is the phonetically natural state for both sonorants and implosives (Ohala, 1983). This can be achieved by the constraint ranking AGREE([voi]), IDENT-ONSET([voi]) >> IDENT([voi])[46]. The ranking is illustrated by the following tableaux for the hypothetical inputs /atga/ and /anta/.

58.

	atga	AGREE([voi])	IDENT-ONSET([voi])	IDENT([voi])
a.	☞ ad.ga			*
b.	at.ga	*!		
c.	at.ka		*!	

In (58), candidate (a), with voicing assimilation triggering a change from [-voice] to [+voice] in the coda, surfaces because it satisfies AGREE([voi]). The coda consonant rather than the onset consonant changes since IDENT-ONSET([voi]) >> IDENT([voi]). Many other repairs could be considered, but these are sufficient to illustrate the argument at hand.

Under this analysis, AGREE must be interpreted to incur a violation if two adjacent segments are specified for [voice] but disagree in its value. Thus, coda [n] fails to incur a violation even if it precedes a voiceless [t], as shown in (59).

59.

	anta	AGREE([voi])	IDENT-ONSET([voi])	IDENT([voi])
a.	an.da		*!	
b.	☞ an.ta			

[46] See Pulleyblank (2002) on agreement and Beckman (1998) on positional faithfulness.

Here, since the fully faithful candidate (b) violates none of the listed constraints, any changes in feature value, such as the change of voicing in (a), will cause a candidate to lose.

3.3.8.2 Comparison of binary and privative voicing

According to a privative voice hypothesis, on the other hand, non-implosive voiced obstruents and possibly sonorants and implosives carry the feature [voice], while voiceless obstruents have no feature assignment for voicing, leaving their phonetic value to be filled in by default; stops and fricatives are, by default, voiceless, since, for them, voicing is difficult to maintain (Ohala, 1983). In syllable coda position, then, the feature [voice] is deleted, and the coda consonant receives any specification for [voice] from the onset of the following syllable. Under such a view, if sonorants and implosives lack a voicing specification, the ranking above still works: AGREE([voi]), IDENT-ONSET([voi]) >> IDENT([voi]). However, the AGREE constraint must be defined differently under this analysis; it is violated if two adjacent consonants differ in their voicing specification, such that one is specified for [voice] and one is not.

The same tableaux also apply for the privative voicing view. In tableau (58), under this interpretation of AGREE, candidate (a), [adga], still wins for input /atga/. The [t] and [g] in the fully faithful candidate violate AGREE since [g] carries a voice feature and [t] does not, and devoicing rather than voicing occurs since faithfulness to onset voicing is ranked higher than faithfulness to coda voicing. Likewise, in (59), the fully faithful candidate surfaces since neither [n] nor [t] have a voicing specification. Under a view of privative voicing where voiced sonorants are specified for [voice], candidate (b) will still surface if a constraint requiring sonorants to be voiced is ranked above IDENT-ONSET([voi]) and is also ranked above AGREE, giving the ranking SONVOICE >> IDENT-ONSET([voi]) >> AGREE([voi]) >> IDENT([voi]).

Since these analyses are strikingly similar, it might seem that the two hypotheses regarding voicing are actually logically equivalent to one another. The tone spreading data, however, show that they actually make different predictions and that the privative voicing hypothesis, in any form, is untenable. As illustrated previously, voicing plays a role in the two tone spreading constraints in Bade in that a high tone spreads unless blocked by a phonologically voiced obstruent and a low tone spreads unless blocked by a voiceless obstruent. The analysis presented above relies on the fact that neither sonorants nor implosives violate the constraints H→¬[+vce] and L→¬[-vce] when they occur within a tone span.

Based on the high tone spreading data alone, one could maintain the privative voice hypothesis: high tone spreading is blocked by the presence of a feature [voice]. However, low tone spreading presents a problem for privative voicing; some feature, or group of features, must be responsible for blocking the tone spreading. Without a voicing specification for voiceless obstruents, the only remaining features that set them apart from sonorants are those that identify these sounds as obstruents, e.g. [-sonorant]. However, relying on the feature [-sonorant] to formulate a constraint for low tone blocking presents a new problem: voiced and voiceless obstruents share identical feature representations apart from the feature [voice], and in particular, if [-sonorant] acts as a tone blocker, then all obstruents, not just voiceless ones, should block low tone spreading. That is, the privative voicing model predicts that, if a voiceless obstruent blocks tone spreading, then the corresponding voiced obstruent will also block tone spreading. Since low tones are free to spread across voiced but not voiceless obstruents in Bade, the predictions of the privative voicing hypothesis are incorrect. Instead, voiceless consonants must be distinguished from voiced ones by having the unique feature designation [-voice]. This [-voice] specification, then, permits voiceless obstruents to be phonologically active while voiced obstruents remain inert with regard to a specific process.

To make this more specific, if only one value of [voice] is available, then, setting aside phonetic grounding issues, the two pairs of constraints found in (60) are the ones that could be of use for Bade; this set of constraints can easily be extended to include implosives.

60. a. H→¬[vce,-son]: No voiced obstruents in a high tone span.
    H→¬[-son]: No obstruents in a high tone span.

    b. L→¬[vce,-son]: No voiced obstruents in a low tone span.
    L→¬[-son]: No obstruents in a low tone span.

In Bade, H→[-son] can be ranked low, since voiceless obstruents, which violate this constraint, do regularly occur in a high tone span. H→¬[vce,-son] effectively prevents voiced obstruents from occurring in a high tone span, so the first set of constraints looks viable.

However, the fact that low tone spreading is blocked by voiceless consonants presents a fatal problem for this analysis. Since low tone spreads across a voiced obstruent, it must be the case that Align(L,Rt) >> L→¬[vce,-son]. However, since low tone does not spread across a voiceless obstruent, we need L→¬[-son]>> Align(L,Rt). This results in a contradiction, since ranking L→¬[-son] above Align(L,Rt) results in a language where a low tone cannot spread across any obstruent at all. Thus, constraints formulated in terms of privative voicing features cannot account for the Bade data.

Furthermore, this cannot be fixed for Bade by using implicational constraints of the type "if voiced, then low", though that approach can account for a relationship between voiceless obstruents and high tone in other languages (Hermans and van Oostendorp, 2000). The constraint L→[vce] is violated by a segment in a low tone span that is not specified for [voice]. This constraint will block low tone spreading over a voiceless obstruent. The corresponding constraint, [vce]→L, is intended to block high tone spreading over voiced obstruents since it is violated by a segment that is specified for voice but is not in a low tone span. Sonorants and implosives, however, are problematic. If these segments are specified for voice, then [vce]→L prevents them from occurring in a high tone span. If they are unspecified for voice, then L→[vce] prevents them from occurring in a low tone span. Under either analysis, then, if L→[vce] and [vce]→L are ranked above ALIGN, as they must be for any blocking to result, then sonorants are incorrectly predicted to block some type of spreading. Again, creating more specific constraints is not helpful; for example, L→[vce,-son] "if low then voiced obstruent" is always violated by a sonorant in a low tone span. Thus, there is no apparent ranking or set of assumptions under which these constraints would be able to account for the Bade data. Also, if a privative voice theory cannot account for Bade phonology, then a unified theory of tone and voice, where there is one privative feature [L/voice] (Bradshaw 1999) will fare no better.

3.3.9 Conclusion

This section provided an in-depth look at consonant-tone interaction in one language. It introduces voice-tone constraints and demonstrates the type of constraint ranking that is necessary in a language where consonants block spreading. I further argue that the Bade system forces reliance on a binary voicing feature.

3.4 Kam

I now provide a second in-depth look at consonant-tone interaction in a language that is typologically quite distinct from Bade. There are no voiced obstruents in Kam, but the data demonstrate consonant-tone interactions involving [constricted glottis] and [spread glottis]. Also, the Kam data provide an example of how tone spans can drive phonotactic consonant-tone interaction.

The phonology of Kam has received even less attention in the literature than Bade has: there are no published theoretical discussions of Kam phonology. The analysis presented here departs significantly from my own previous work on the language (Schack, 2003). The data in this paper are based on descriptions of the standard variety of Southern Kam, also called Dong (Long & Zheng, 1988; Zheng & Yang, 1988). The basic pattern described here is confirmed by my own work on the language, and the tone system itself has been verified experimentally (Edmondson, 1992).

3.4.1 Descriptive phonology

Kam has nine tones: 55, 33, 11, 35, 453, 53, 323, 13, and 31 (where 1 is low and 5 is high). These are fully contrastive in certain environments, as shown by the minimal set in (61):

61.	[saw^{55}] 'twist'	[saw^{323}] 'stream (v)'	[saw^{53}] 'soup'
	[saw^{11}] 'rear (v)'	[saw^{31}] 'husband'	[saw^{33}] 'create'
	[saw^{35}] 'straw'	[saw^{13}] 'grass carp'	[saw^{453}] 'egret'

I assume these tones are represented phonologically by register (H, L) and contour (h, l) features (cf. Bao 1990 et seq, Yip 1989 et seq), as described in Section 1.1.[47] The phonological representation for the nine tones is given in Table 5.

	Level	*Rising*	*Falling*	*Complex*
Low register	11 (L, l)	13 (L, lh)	31 (L, hl)	323 (L, hlh)
High register	55 (H, h)	35 (H, lh)	53 (H, hl)	453 (H, lhl)
	33 (H, l)			

Table 5. Phonological Representation of Kam Tones

Although tone [33] could potentially belong to either high or low register based on its phonetic realization, it clearly patterns with the high register tones phonologically, as will be seen in Table 10, and is therefore considered a high register, low contour tone.

Syllable structure and consonant type both affect the type of tone that is permitted to surface. A Kam syllable is minimally bimoraic and may be of the shape CV:, CVC, or CV:C. The eight phonemically distinct vowels are given in (62).

62. Short ə, ɐ, o
    Long i:, e:, a:, o:, u:

Table 6 lists the syllable initial consonants found in native vocabulary.

[47] The Kam tones do not require a further distinction of mid or neutral tone/register.

Voiceless aspirated stops	p^{h}, p^{jh}, t^{h}, $tɕ^{h}$, k^{h}, k^{wh} [48]
Voiceless unaspirated stops	p, p^{j}, t, tɕ, k, k^{w}, ʔ
Fricatives	s, ɕ, χ, $χ^{w}$ [49]
Nasals	m, m^{j}, n, ɲ, ŋ, $ŋ^{w}$
Liquids	l, l^{j}
Glides	j, w

Table 6. Kam Initials

Final consonants are a limited subset of the initials: $p^{ʔ}$, $t^{ʔ}$, $k^{ʔ}$, m, n, ŋ, w, j. All final obstruents are glottalized.

3.4.2 Restrictions on tone distribution

On certain types of syllables, all tones are allowed to occur. However, if there is a stop in either the onset or the coda, the number of possible tones is limited considerably.

Onset-tone restrictions result from aspiration, as Table 7 and Table 8 show.

	Tone	*Initial Rise*			*Initial fall*			*Level*		
Onset		35	13	453	323	31	53	11	33	55
Aspirated stop			✓							

Table 7. Aspiration-Tone Restrictions

After an aspirated stop, rising tones 35, 13, and 453 occur. For example, [$p^{h}aː^{35}$] ‘grey’ is a Kam word but [$*paː^{35}$] is ungrammatical.

[48] Edmondson (1992) includes [ɦ] as well; Zheng and Long (1988) include [ʔɦ].
[49] This is usually written as [h], but according to Long and Zheng (1998), the actual place of articulation is “somewhere between velar and glottal, close to the uvular sound”(22).

	Tone	*Initial Rise*			*Initial fall*			*Level*		
Onset		35	13	453	323	31	53	11	33	55
Unspirated stop						✓			✓	

Table 8. Restrictions on Plain Stops and Tones

After an unaspirated stop, all other tones occur. Here, [*paː^{35}] is ungrammatical, but [paː^{55}] ‘fish’ is grammatical.

After other onsets, all tones occur, as shown in

	Tone	*Initial Rise*			*Initial fall*			*Level*		
Onset		35	13	453	323	31	53	11	33	55
Sonorant, Fricative, ʔ			✓			✓			✓	

Table 9. All Tones after Other Onsets

The glottal stop patterns with the sonorant and fricative rather than with the voiceless unaspirated obstruents.

Rhyme-tone restrictions, on the other hand, result from glottalization and vowel length; Table 10 shows these restrictions on syllables that have no onset restrictions.

	Tone				*Low Reg.*			*High Reg.*			
Onset		55	11	35	323	31	13	53	33	453	Rhyme
Sonorant, Fricative, ʔ		✓	✓	✓	✓	✓	✓	✓	✓	✓	V(:)(S)
					✓	✓	✓				V:O
		✓	✓	✓							VO

Table 10. Rhyme-Tone Restrictions

If the syllable is checked, that is, if it ends in a glottalized stop, the high register tones 53, 33, and 453 do not occur; for example, *[soːtˀ ^{53}] is not found but [soːtˀ ^{31}] ‘vanish’ is grammatical. The tones that do occur in these syllables depend on the vowel length. The low register tones 323, 13, and 31 do not occur on short vowels; [*wətˀ ^{31}] is not a possible word in Kam but [we:tˀ ^{31}] ‘blow’ exists. On the other hand, tones 55, 35, and 11 do not occur on long vowels; *[meːtˀ ^{11}] is ungrammatical but [mətˀ ^{11}] ‘ant’ is a word. If the syllable does not end in a stop, all tones occur.

These co-occurrence restrictions are summarized in Table 11.

Onset / Tone	55	11	35	323	31	13	53	33	453	Rhyme
Aspirated stop			✓			✓			✓	V(:)(Sonorant)
						✓				V:Obstruent
			✓							VO
Unaspirated stop	✓	✓		✓	✓		✓	✓		V(:)(S)
				✓	✓					V:O
	✓	✓								VO
Sonorant or fricative	✓	✓	✓	✓	✓	✓	✓	✓	✓	V(:)(S)
				✓	✓	✓				V:O
	✓	✓	✓							VO

Table 11. Co-occurrence Restrictions in Kam

3.4.3 Analysis of Kam

I now turn to an account of consonant-tone interaction in Kam. Because of the large number of tones, I limit the analysis here to tones that are part of the language’s phonetic tone inventory rather than considering the factors that shape this inventory. Moreover, with one exception, addressed in Section 3.4.3.1, I limit my analysis to those restrictions that are specifically related to consonants; in particular, in Section 3.4.3.8 I argue that tone [11] failing to occur in CV:O syllables and tone [33] failing to occur in CVO syllables are not directly related to consonant type.

I make several other basic assumptions about the data. First, I assume that register and contour are hierarchical in Kam; specifically, the contour domain must be a subset of the register domain. I do not consider candidates that do not meet this description. I further assume that the basic domain of the register is the rhyme while the basic domain of the contour is the mora, though different domains and alignments are possible and do surface in the language. Finally, I consider only candidates with one register per syllable; that is, all syllables must be marked for register, and there are no cross-register tones. I assume spans at the same level are arranged linearly and are non-overlapping. To the extent that other representations are cross-linguistically possible, they must be prevented by high-ranked constraints in Kam, but I do not include these in the tableaux or general ranking.

I also follow several conventions to keep the tableaux as clear as possible. Since register and contour do not interact with each other, I provide the alignment only for the tone feature under direct consideration. I assume that the register domain does not change on candidates where contour is under consideration and vice versa, with one exception: if additional segments are included in the domain of a contour tone, I assume that the domain of the register tone expands to include these syllables. I continue the convention of marking register with H, L and contour with h, l. The tone numbers are also provided for clarity, although these are not considered phonological entities—they merely provide an approximate indication of the phonetic interpretation of the candidate.

3.4.3.1 Contour tones and CVO syllables

With the exception of tone [35], no contour tones occur on CVO syllables such as *[wət^{ʔ} ^{31}]. This follows from a constraint against contour tones on the language's least sonorous rhymes. This constraint draws on the results of Zhang's (2002) survey, in which it is shown that contour tones prefer syllables of greater canonical duration, i.e., syllables with a longer sonorous portion. Thus, the least sonorous rhymes in Kam block contour tones altogether. The constraint is formulated in (63).

63. *CONTOUR/CVO: A contour tone cannot occur on a CVO syllable.

This constraint must be ranked higher than some faithfulness constraint in order to prevent *[wətˀ ^{31}] from surfacing. In (64), this is accomplished by ranking *CONTOUR/CVO >> IDENT-V.

64.

w[ə]$_l$[t]$_h$$^{L\ 13}$	MAX-T	*CONTOUR/CVO	IDENT-V
a. w[ə]$_l$[tˀ]$_h$$^{L\ 13}$		*!	
b. w[ətˀ]$_l$$^{L\ 11}$	*!		
c. ☞w[e]$_l$[:tˀ]$_h$$^{L\ 13}$			*

The input in (64) , like that of future tableaux, includes the tonal information not manipulated in the given candidates as a superscript at the end of the input form. This input has the register tone Low and the contour tones lh, corresponding to tone [13]. I also assume a high-ranked constraint requiring coda obstruents to be glottalized.

3.4.3.2 High register tones and checked syllables

There are no words like *[soːtˀ ^{55}] with a high register tone occurring on a long vowel in a checked syllable. This results from a high ranked constraint requiring that a high register span not contain a segment with the feature [constricted glottis].

65. **H→¬[cg]**: A high register span cannot contain a segment with the feature [+constricted glottis] (cf. Morén and Zsiga 2006).

Although this constraint has the same phonetic basis as a similarly formulated L→[cg] or [cg]→L, it will become clear that neither of these constraints would have the correct result in Kam because only certain high register tones are completely banned in checked syllables.

This portion of the analysis relies crucially on the syllable structure in Kam. As previously indicated, Kam syllables must be bimoraic since there are no syllables of the shape CV. Moreover, coda consonants are moraic, since there are syllables of the shape CVC. Thus, in a bimoraic syllable of the shape CV:C, the second mora is shared between the vowel and the coda consonant. This is the crucial difference in structure between a CVO and a CV:O syllable; the difference is illustrated in (66).

66. (a) CVO syllable (b) CV:O syllable

(a)	(b)
$[\mu\ \mu]_{Reg}$	$[\mu\ \ \mu]_{Reg}$
| |	| / |
V O	V : O

The default register alignment, given in (66), includes the entire bimoraic rhyme in its span. However, this presents a dilemma for a high register tone since both (a) and (b) violate the constraint $H \rightarrow \neg[cg]$. One possible repair is for the register value to be changed to low. This, however, cannot be the full solution in Kam since two high register tones, [55] and [35] do occur in certain checked syllables. A second possible repair is to realign the register span. In (66a) this is straightforward; the span can be associated with the first mora, which in turn corresponds to the vowel. However, in (66b), this is not the case. If the register span is aligned only to the first mora, then a portion of the vowel is not included in a tone span at all. On the other hand, if the span is aligned to the vowel, it no longer matches the moraic structure.

The solution adopted here conceptually follows Morén and Zsiga's (2006) analysis of Thai. Like Kam, Thai has only CV:, CVC, and CV:C syllables, with tone restrictions on CV:C syllables. Thai has five tones, often described as high, mid, low, falling, and rising. Based on their phonetic work, Morén and Zsiga analyze these tones as follows—high: $\mu[\mu]_H$, mid: $\mu\mu$, low: $\mu[\mu]_L$, falling: $[\mu]_H[\mu]_L$, and rising: $[\mu]_L[\mu]_H$. Only those tones with a low tone associated to the second mora are permitted in CV:O syllables, a fact which the authors account for with the constraint C.G.CODA→L "Constricted glottis segments must be associated with a low tone" (p. 143). CVO syllables, on the other hand, permit both low and high tones, a fact which requires a different solution in Thai than the one presented here for Kam.

In particular, in Kam, the constraint H→¬[cg] is unviolated by the winning candidate. In addition, two constraints on alignment, VINSPAN and SPAN⊇MORA (38), and a faithfulness constraint, IDENT-REG, are all ranked higher than IDENT-V. The new constraints are defined below.

67. VINSPAN: Any mora associated with a vowel must be included in a tone span.

68. IDENT-REG: The feature value of a register span in the input must match the feature value of a corresponding register span in the output.

69. IDENT-V: The feature value of a vowel in the input must match the feature value of a corresponding vowel in the output.

Because of this ranking, *[soːtˀ ⁵⁵] is not permitted, as shown in (70). In the fully faithful candidate, the high register span contains the mora that is attached to the glottalized [tˀ], thereby violating H→¬[cg].

70.

s[oːt]$_{H}^{h\ 55}$	H→¬[cg]	VINSPAN	SPAN⊇MORA	IDENT-REG	IDENT-V
a. s[oːtˀ]$_{H}^{h\ 55}$	*!				
b. s[oːtˀ]$_{L}^{h\ 33}$				*!	
c. s[oː]$_{H}$tˀ$^{h\ 55}$			*!		
d. s[o]$_{H}$ːtˀ$^{h\ 55}$		*!			
e. ☞s[o]$_{H}$tˀ$^{h\ 55}$					*

All of the other candidates with a long vowel violate a constraint ranked higher than IDENT-V, as seen in the tableau: changing register, aligning the register to the vowel, or omitting a portion of the vowel from the register span are all impermissible repairs. Consequently, the winning candidate is the one with a short vowel; the short vowel makes it possible for the register span to not include the final consonant without violating the alignment constraints SPAN⊇MORA and VINSPAN. While the second candidate, s[oːtˀ]$_{L}$, is a grammatical output in Kam, the ranking IDENT-V >> IDENT-REG proves to be untenable in light of the rest of the data.

However, the winning candidate does violate other constraints on alignment. [pokˀ^{55}] 'frame up', with a short vowel, is a possible word, as shown in (73), but the winning candidate violates IDENT-RALIGN, and by assumption IDENT-CALIGN, defined below.

71. IDENT-RALIGN: The alignment of a register span in the input must match the alignment of the corresponding register span in the output. Incurs one violation for each register edge aligned differently in the output than in the input.

72. IDENT-CALIGN: The alignment of a contour span in the input must match the alignment of the corresponding contour span in the output. Incurs one violation for each register edge aligned differently in the output than in the input.

This establishes that H→¬[cg], IDENT-REG >> IDENT-RALIGN, IDENT-CALIGN.

73.

p[ok]$_{H}^{h\ 55}$	H→¬[cg]	IDENT-REG	IDENT-RALIGN	IDENT-CALIGN
a. ☞p[o]$_{H}$k$^{ʔ\ h\ 55}$			*	*
b. p[okʔ]$_{H}^{h\ 55}$	*!			
c. p[okʔ]$_{L}^{h\ 33}$		*!		

Given the high ranking of *CONTOUR/CVO, it is surprising that tone [35] is permitted on CVO syllables. This is not the only peculiarity in the distribution of this tone; while tone [13] is permitted on CVːO syllables, tone [35] is blocked in this environment. Thus, [p^{h}ok$^{ʔ\ 35}$] ‘time’ and [p^{h}oːk$^{ʔ\ 13}$] ‘cast away’ are words, but *[p^{h}ok$^{ʔ\ 13}$] and *[p^{h}oːk$^{ʔ\ 35}$] are non-words. This follows, however, from the ranking already established, where MAX-T, H→¬[cg], *CONTOUR/CVO, IDENT-REG >> IDENT-V. This ranking predicts that the vowel length distinction will be neutralized in obstruent-final syllables in order to accommodate the correct tone pattern. The tableaux for these words are found in the following section; before illustrating these patterns, it is helpful to establish a ranking that yields the basic distribution of rising tones in Kam.

3.4.3.3 Aspirated onsets and rising tone

Aspirated onsets in Kam must precede a rising tone, and non-aspirated obstruents cannot precede a rising tone. If consonant-tone interaction requires coinciding tone spans and consonant specifications, this means that onset restrictions require the onset to be contained in a contour span in Kam. In particular, then, I argue that the connection between initial aspiration and rising tone results from two constraints, [sg]→l and l→[sg]:

74. [sg]→l: A consonant that is [+spread glottis] must be located in a low contour span.

75. l→[sg]: A consonant that is located in a low contour span must have the feature specification [+spread glottis].[50]

Depending on the input, a high ranking of the first of these constraints forces either the realignment of the existing tone spans or the insertion of a low tone span so that the onset will be included in a low tone span.

In the case of an input like *[p^{h}aː^{55}], the ranking [sg]→l, IDENT-CALIGN, IDENT-LAR >> DEP-T (35), with IDENT-LAR defined in (76), results in the insertion of a low tone.

76. IDENT-LAR: If a consonant has a laryngeal feature specification in the input and the corresponding consonant has a laryngeal feature specification in the output, these two feature specifications must be identical.

This ranking is illustrated in (77). The final candidate in (77) violates IDENT-CALIGN, but the winning candidate does not since the low span is inserted rather than realigned. However, since both of these candidates include the onset in a contour tone span, then by assumption, the register span is also realigned to include the onset for that candidate, meaning that both candidates violate IDENT-RALIGN as well. This yields the ranking [sg]→ l, IDENT-LAR, IDENT-CALIGN >> IDENT-RALIGN.

77.

p^{h}[aː]$_{h}^{H\ 55}$	[sg]→ l	IDENT-LAR	IDENT-CALIGN	DEP-T	IDENT-RALIGN
a. p^{h}[aː]$_{h}^{H\ 55}$	*!				
b. ☞[p^{h}]$_{l}$[aː]$_{h}^{H\ 35}$				*	*
c. p[aː]$_{h}^{H\ 55}$		*!			
d. [p^{h}aː]$_{l}^{H\ 33}$			*!		*

I assume, then, that the phonetics is able to reinterpret a tone span including only an obstruent in its domain so that the tone is at least partially realized on the

[50] More generally, these constraints could be formulated in terms of segments rather than consonants, potentially resulting in a connection between breathy voice and low tone. However, since this thesis does not address vowel quality issues, I provide more specific constraints.

adjacent vowel, so that the optimal output from this tableau will still result in the surface interpretation [p^haː^{35}]. While the low tone cannot be perceived on the obstruent, the prediction, based on a direct phonetic implementation of spans, is that the low is phonetically aligned with the syllable onset; by the time the vowel onset is reached, F0 will already begin to move towards the high target, resulting in a phonetically rising tone. A more abstract phonetic interpretation would interpret any low-high sequence of tones as a rising tone rather than a sequence of two level targets, but again, the prediction is that a portion of the rise will be inaudible due to the obstruent onset. However, since the phonetic data needed to understand tone alignment in Kam is not currently available, I focus here on the type of phonological representation that is needed in order to systematically account for these data.

While the constraint [sg]→ l triggered the insertion of a low tone in the previous example, this constraint alone cannot account for the full distribution of rising tones in Kam, since it can only be violated by a candidate that includes an aspirated consonant. To explain the fact that *[pa^{35}] also fails to occur, the converse constraint, l→[sg], acts in conjunction with *RISE, defined below:

78. *RISE: Violated by the configuration $[\mu]_l[\mu]_h$

*RISE is more specific than *CONTOUR/CVO in that it specifically addresses rising tone, but it places no restrictions on the combination of segments in the syllable. The maximum rate of rising F0 production is slower than the maximum rate of falling F0 production (Y. Xu & Sun, 2002), so this constraint is phonetically grounded. While it may seem somewhat peculiar that a possible repair to this constraint is to place a span on the onset instead of on the coda, to the extent that span onset serves as a phonetic cue, this does increase the time given for the vocal folds to respond and produce a rising tone.

The tableau in (79), then, shows how an input like *[pa:^{35}] is treated by the grammar. Specifically, the ranking MAX-T, *RISE, [sg]→ l, l→[sg] >> IDENT-LAR, IDENT-CALIGN results in this output. While the exact ranking of IDENT-CALIGN cannot be established, it must be ranked below [sg]→ l and *RISE to keep the wrong candidate from surfacing—though, again, without experimentation, it is unknown whether there is more than a theoretical difference between *p^h[a]$_l$[a]$_h$ and [p^h]$_l$[a:]$_h$.

79.

p[a]$_l$[a]$_h$$^{H\ 35}$	MAX-T	[sg]→ l	l→[sg]	*RISE	IDENT-LAR	IDENT-CALIGN
a. p[a]$_l$[a]$_h$$^{H\ 35}$				*!		
b. ☞[p^h]$_l$[a:]$_h$$^{H\ 35}$					*	*
c. p[a:]$_h$$^{H\ 55}$	*!					*
d. [p]$_l$[a:]$_h$$^{H\ 35}$			*!			*
e. p^h[a]$_l$[a]$_h$$^{H\ 35}$		*!		*		

This now provides us with the background needed to address the distribution of rising tones in checked syllables. The tableau in (80) shows that in a CVO syllable, tone [13] is blocked since it violates *CONTOUR/CVO. The violation is alleviated by lengthening the vowel in the winning candidate rather than leveling the contour, as in the third candidate, since MAX-T, *CONTOUR/CVO >> IDENT-V. The constraint [sg]→ l eliminates candidates like (d), where the low tone is not aligned to the onset.

80.

p^h[o]$_l$[k]$_h$$^{L\ 13}$	[sg]→ l	MAX-T	*CONTOUR/CVO	IDENT-V
a. [p^h]$_l$[ok^ʔ]$_h$$^{L\ 13}$			*!	
b. ☞[p^{h}o]$_l$[:k^ʔ]$_h$$^{L\ 13}$				*
c. [p^{h}ok^ʔ]$_l$$^{L\ 11}$		*!		
d. p^h[o]$_l$[:k^ʔ]$_h$$^{L\ 13}$	*!			

This alignment of a rising tone to the onset also permits tone [35] to surface in a CVO syllable. This is because [35] is a high register tone; lengthening the vowel, as in the second candidate, now causes the high register span to include the glottalized coda. Since neither this candidate, nor the final candidate with lengthened vowel and lowered register, is permitted to surface, this means that H→¬[cg], IDENT-REG, MAX-T >> *CONTOUR/CVO.

81.

$p^h[o]_l[k]_h{}^{H\ 35}$	H→¬[cg]	IDENT-REG	MAX-T	*CONTOUR / CVO	IDENT-V
a. ☞ $[p^h]_l[o]_h k^{ʔ\ H\ 35}$				*	
b. $[p^h o]_l[ːk^ʔ]_h{}^{H\ 35}$	*!				*
c. $[p^h o]_l k^{ʔ\ H\ 33}$			*!		
d. $[p^h o]_l[ːk^ʔ]_h{}^{L\ 13}$		*!			*

Only the candidates that adhere to the ranking of alignment constraints already established in (70) and (79) are included in this tableau.

Finally, given the considering the behavior illustrated in (79) and (81), we predict that an input like *[$p^h ok^{11}$] should surface as [$p^h oːk^{13}$]. This follows from the ranking for (79), with the addition of IDENT-LAR, IDENT-CALIGN >> IDENT-V. Now the fully faithful candidate fails to surface because it violates [sg]→ l. If a low tone is inserted, as in the final candidate, it still violates *CONTOUR/CVO. The removal of the initial aspiration causes a violation of IDENT-LAR in the fourth candidate, and realigning the low span to include the onset violates IDENT-CALIGN in the third candidate. Consequently, the first candidate, where a span is inserted and the vowel is lengthened, surfaces.

82.

$p^h[ok]_l{}^L$	[sg]→ l	*CONTOUR / CVO	IDENT-LAR	IDENT-CALIGN	IDENT-V
a. ☞ $[p^h]_l[o{:}k^ʔ]_h{}^{L\ 13}$			*		*
b. $p^h[ok^ʔ]_l{}^{L\ 11}$	*!		*		
c. $[p^hok^ʔ]_l{}^{L\ 11}$			*	*!	
d. $p[ok^ʔ]_l{}^{L\ 11}$			*!*		
e. $[p^h]_l[ok^ʔ]_h{}^{L\ 13}$		*!	*		

I assume, in the first and last candidates, that the initial span is inserted and that the span that includes the rhyme has been changed in value from low to high. Thus, both violate the constraints DEP-T and IDENT-C. These constraints are omitted from the tableau, but both must be ranked below IDENT-LAR and IDENT-CALIGN. IDENT-C is defined below.

83. IDENT-C: The feature value of a contour span in the input must match the feature value of a corresponding contour span in the output.

3.4.3.5 Falling tones

The analysis thus far implies that falling tones should have similar behavior to rising tones since both violate *CONTOUR/CVO, but this is not the case. For example, if a falling tone is substituted for a rising tone in tableau (81), the prediction is that the ungrammatical *$[pok^{53}]$ will surface.

84.

$p[o]_h[k]_l{}^{H\ 53}$	H→¬[cg]	IDENT-REG	MAX-T	*CONTOUR/ CVO	IDENT-V
a. !☞ $[p]_h[o]_lk^{ʔ\ H\ 53}$				*	
b. $[po]_h[{:}k^ʔ]_l{}^{H\ 53}$	*!				*
c. $[po]_hk^{ʔ\ H\ 55}$			*!		
d. $[po]_h[{:}k^ʔ]_l{}^{L\ 31}$		*!			*

Thus, a more specific constraint than *CONTOUR/CVO is needed to block falling tones from occurring on syllables of low canonical duration; *FALL/CVO is defined in (85).

85. *FALL/CVO: A falling tone cannot occur on a CVO syllable.

It is somewhat surprising that *FALL/CVO would outrank a similarly defined *RISE/CVO—this constraint would need to be ranked high like *CONTOUR/CVO—since rising tones take longer to produce than falling tones do, and consequently an a priori ranking might be expected. Nevertheless, in Kam, it is quite clear that rising tones, but not falling tones, are permitted on CVO syllables.

The only grammatical candidate in (84) is the final one, which is realized as [po:k^{31}]. In order for it to surface, the constraint *FALL/CVO must be ranked with H→¬[cg] and MAX-T above IDENT-REG. The new tableau is given in (86).

86.

$p[o]_h[k]_l^{H\ 53}$	H→¬[cg]	*FALL/CVO	MAX-T	IDENT-REG	*CONTOUR / CVO
a. $[p]_h[o]_l k^{ʔ\ H\ 53}$		*!			*
b. $[po]_h[:k^ʔ]_l^{H\ 53}$	*!				
c. $[po]_h k^{ʔ\ H\ 55}$			*!		
d. ☞ $[po]_h[:k^ʔ]_l^{L\ 31}$				*	

3.4.3.6 Onsets with no restrictions

According to the ranking so far, rising tones should only follow aspirated onsets. However, these restrictions do not apply to glottal stops, sonorants, and fricatives, implying that high-ranked markedness constraints for [spread glottis] on segments other than (non-glottal) stops are needed; (87) and (88) formulate these constraints specifically for [spread glottis] on sonorant and glottal segments.

87. *[sg]/[son]: Violated by a segment that is both sonorant and [+spread glottis].

88. *[sg]/[cg]: Violated by a segment that is both [+spread glottis] and [+constricted glottis].

All three of these constraints are common cross-linguistically.

The tableau in (89) demonstrates how the constraint *[sg]/[son] works for [maːn[13]] ‘Chinese fir’. This form is grammatical when *[sg]/[son], MAX-T, and l→[sg] are ranked above *RISE. This also further establishes the low ranking of IDENT-CALIGN.

89.

$m[a]_l[ːn]_h^{L\ 13}$	*[sg]/[son]	MAX-T	l→[sg]	*RISE	IDENT-LAR	IDENT-CALIGN
a. ☞$m[a]_l[ːn]_h^{L\ 13}$				*		
b. $[m^h]_l[aːn]_h^{L\ 13}$	*!				*	***
c. $m[aːn]_l^{L\ 11}$		*!				*
d. $[m]_l[aːn]_h^{L\ 13}$			*!			***

Here, the winning candidate violates *RISE. However, realigning the low tone to the onset, as in the final candidate, cannot alleviate this violation because this violates l→[sg]. Fixing the final candidate by aspirating the onset results in a violation of *[sg]/[son], while deleting a tone results in a violation of MAX-T. Since all three of these constraints outrank *RISE, the faithful candidate surfaces.

3.4.3.7 Syllable structure and consonant type

One remaining issue for the Kam tone system is that the consonant-tone constraints introduced here are sensitive not only to tone type but also to syllable structure. [spread glottis] never occurs on final obstruents, even when these sounds are in a low contour span, and [constricted glottis] freely occurs with all tones in onset position, even when the preceding analysis predicts that these segments should be included in a high register span.

The ranking established thus far also makes it impossible to realign the spans in order to permit the offending segment to surface without being included in a tone span. Moreover, a high ranked constraint against [constricted glottis] and [spread glottis] occurring on the same segment, while certainly plausible, is ineffective in this regard.

To make this more concrete, the syllable [ʔat^{ʔ} ^{35}] is grammatical in the language, but based on (89), we would expect this input to surface as ʔ$[a]_l[:t^{ʔ}]_h$ in a low register. There are two potential problems with the input form: the glottal stop is unaspirated, violating l→[sg], and it is in a high register span, violating H→¬[cg]. The tableau in (90) illustrates this difficulty; the current ranking predicts that [ʔat^{ʔ} ^{35}] can never surface in the language.

90.

ʔ$[a]_l[t]_h^{H\ 35}$	H→¬[cg]	MAX-T	l→[sg]	IDENT-REG	*RISE	IDENT-LAR
a. ʔ$[a]_l[t^{ʔ}]_h^{H\ 35}$	*!				*	
b. $[ʔ^{h}]_l[a]_h t^{ʔ\ H\ 35}$	*!					*
c. ʔ$[at^{ʔ}]_l^{H\ 33}$	*!	*				
d. $[ʔ]_l[a]_h t^{ʔ\ H\ 35}$	*!		*			
e. !☞ ʔ$[a]_l[:t^{ʔ}]_h^{L\ 13}$				*	*	

In other words, this tableau shows that a glottal stop in onset position is predicted to have the same interactions with tone as a glottal stop in coda position. The final candidate wins because it is the only candidate that is able to alleviate all violations of H→¬[cg] without deleting a tone. The fact that glottal stop in onset actually fails to interact with tone at all indicates that constraints on consonant-tone interaction must, in some cases, be limited to a specific syllable position, here, coda. The more specific constraint is given in (91).

91. H→¬$[cg]_{Coda}$: A coda consonant that is located in a high register span must not have the feature specification [+constricted glottis].

Similarly, since l → [sg] is freely violated by coda consonants, a more specific version of (75), found in (92), is needed.

92. l→$[sg]_{Ons}$: An onset consonant that is located in a low contour span must have the feature specification [+spread glottis].

The new constraints do not invalidate the rankings given in previous sections, since they involved only candidates that violate the positional version of the constraint.

The updated version of (90) is found in (94). While the ranking H→¬$[cg]_{Coda}$, MAX-T >> IDENT-REG was established in (86), no ranking between IDENT-REG and l→$[sg]_{Ons}$ has thus far been required. However, in order that the final candidate not be optimal, IDENT-REG must be ranked higher than l→$[sg]_{Ons}$. In addition, *[sg]/[cg] is included in the tableau; this constraint is unviolated in this dialect of Kam and therefore undominated as well. Finally, the undominated constraint IDENT-PLACE, defined in (93), prevents the candidate with the permissible aspirated onset [k^h] from surfacing.

93. IDENT-PLACE: If a consonant in the input corresponds to a consonant in the output, their place specifications must match.

With this ranking, the grammatical word [ʔat$^{ʔ\ 35}$] is permitted to surface.

94.

ʔ$[a]_l[t]_h^{H\ 35}$	H→ ¬$[cg]_{Coda}$	*[sg]/ [cg]	IDENT-PLACE	MAX-T	IDENT-REG	l→ $[sg]_{Ons}$	*RISE	IDENT-LAR
a. ʔ$[a]_l[t^ʔ]_h^{H\ 35}$	*!						*	
b. $[ʔ^h]_l[a]_h t^{ʔ\ H\ 35}$		*!						*
c. ʔ$[at^ʔ]_l^{H\ 33}$	*!			*				
d. ☞$[ʔ]_l[a]_h t^{ʔ\ H\ 35}$						*		
e. ʔ$[a]_l[t^ʔ]_h^{L\ 13}$					*!		*	
f. $[k^h]_l[a]_h t^{ʔH\ 35}$			*!					**

3.4.3.6 Convex and concave tones

Although it is not specifically my purpose to argue for the basic tone system of Kam, it is important to show that the analysis here does not exclude the three-way contour tones [453] and [323]. There are various ways of approaching these tones, but the ranking thus far permits them to surface so long as they are equally distributed across the segments of the word. Since SPAN⊇MORA is undominated in the ranking, this prohibits multiple tone spans from occurring on one mora, forcing the third span to be realized on the onset. Since [453] behaves like a rising tone with respect to aspirated onsets and [323] like a falling tone, no contradictions to [sg]→l and l→[sg] result from this aligntment.

The ranking of SPAN⊇MORA, MAX-T above a basic structural constraint like ALIGN(REG,RHYME) is sufficient to permit tone [323] to surface on a syllable like [kam], as shown in (96).

95. ALIGN(REG,RHYME): The domain of the register is the rhyme. This incurs one violation for each register boundary that is not aligned to the edge of the rhyme.

Here, the winning candidate violates only ALIGN(REG,RHYME) and *RISE. The repairs to the other two candidates, deleting or realigning the tone, are not permitted because they violate the undominated constraints MAX-T and SPAN⊇MORA.

96.

$[k]_h[a]_l[n]_h^{L\ 323}$	MAX-T	SPAN⊇MORA	ALIGN(REG,RHYME)
a. ☞ $[k]_h[a]_l[n]_h^{L\ 323}$			*
b. $k[a]_l[n]_h^{L\ 13}$	*!		
c. $k[a]_{hl}[n]_h^{L\ 323}$		*!	

Similarly, the ranking SPAN⊇MORA, MAX-T >> l→$[sg]_{Ons}$ >> ALIGN(REG,RHYME) causes an input syllable with the same segmental structure and tone [453] to surface with an aspirated onset, as shown in (97).

97.

$[k]_l[a]_h[m]_l$ $^{H\ 453}$	MAX-T	SPAN⊇MORA	$l \rightarrow [sg]_{Ons}$	ALIGN(REG,RHYME)
$[k]_l[a]_h[m]_l^{H\ 453}$			*!	*
$k[a]_h[m]_l^{H\ 53}$	*!			
$k[a]_{lh}[m]_l^{H\ 453}$		*!		
☞ $[k^h]_l[a]_h[m]_l^{H\ 453}$				*

Now, the fact that the onset is unaspirated causes the first candidate to violate $l \rightarrow [sg]_{Ons}$, and so the final candidate, with aspiration added to the onset, surfaces.

3.4.3.7 Summary constraint ranking

To summarize, I have argued for roughly the following ranking; not all individual relationships between constraints in different strata hold:

98. Stratum 1: SPAN⊇MORA, MAX-T, *[sg]/[cg], H→¬[cg]$_{Coda}$, *FALL/CVO, [sg]→l, *[sg]/[son], IDENT-PLACE
Stratum 2: IDENT-REG
Stratum 3: $l \rightarrow [sg]_{Ons}$, *CONTOUR/CVO
Stratum 4: *RISE
Stratum 5: IDENT-LAR, IDENT-cALIGN
Stratum 6: DEP-T, IDENT-RALIGN, IDENT-V, ALIGN(REG,RHYME), IDENT-C

This ranking was checked in OTSoft (Hayes, Tesar, & Zuraw, 2003), generating the Hasse diagram on the following page.

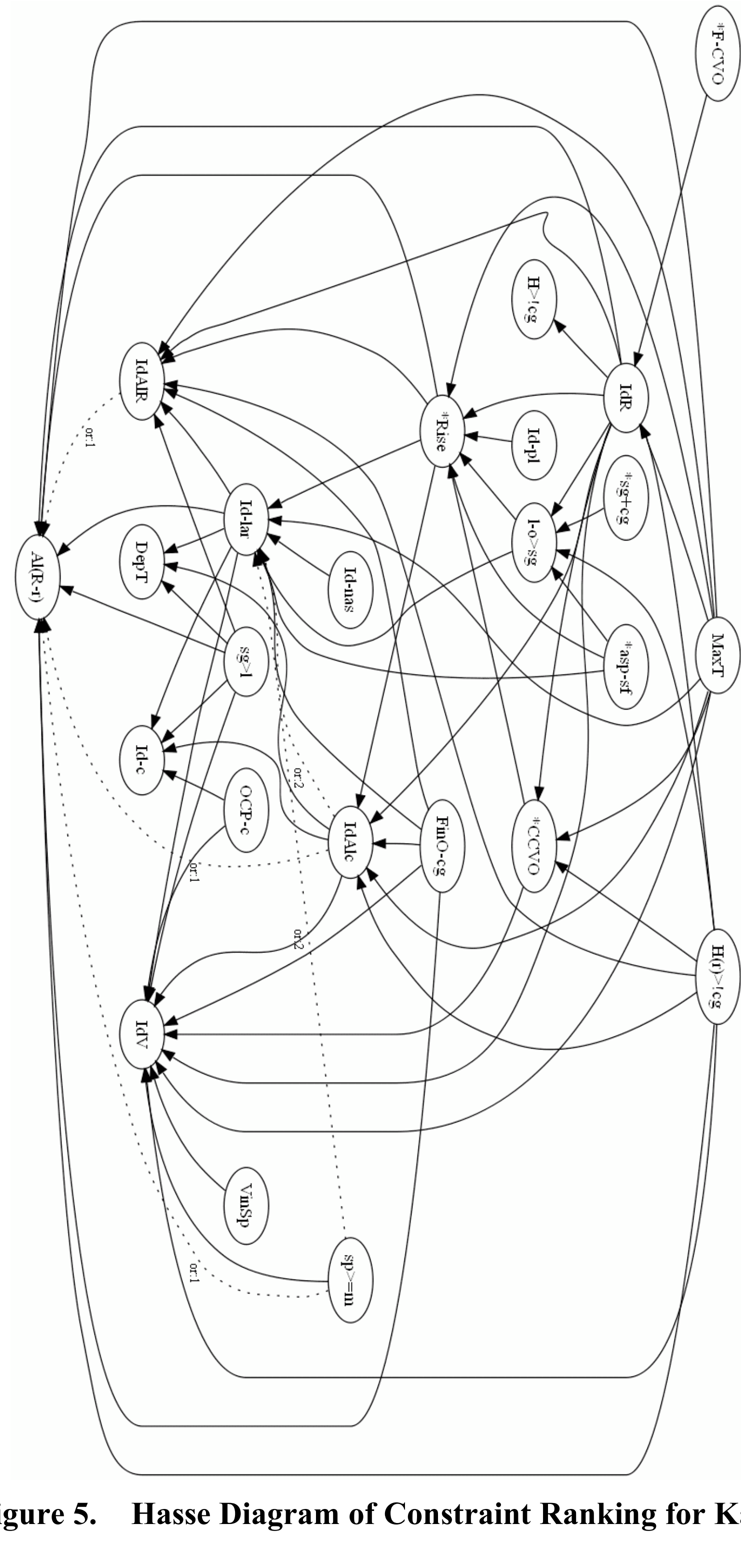


Figure 5. Hasse Diagram of Constraint Ranking for Kam

The Hasse diagram includes several constraints that are not included in tableaux in the text:

99. OCP-C: Adjacent contour tones tones must not be identical.

100. IDENT-NASAL: If a segment in the input has a corresponding segment in the output, they must have identical values for the feature [nasal].

101. FINALOBS→[cg]: An obstruent in coda position must be [+constricted glottis].

Finally, the table below, essentially repeated from Table 11, shows a simplified version of the analysis, indicating the basic constraints that trigger co-occurrence restrictions in Kam. A check indicates that a combination is permitted; a shaded box indicates that a combination is not permitted.

T / Ons	55	11	35	323	31	13	53	33	453	Rhyme
p^h	sg→l	sg→l	✓	sg→l	sg→l	✓	sg→l	sg→l	✓	V(:)(S)
	sg→l	sg→l	H→ ¬cg	sg→l	sg→l	✓	sg→l	sg→l	sg→l	V:O
	sg→l	sg→l	✓	sg→l	sg→l	*Con/ CVO	sg→l	sg→l	sg→l	VO
p	✓	✓	l→sg	✓	✓	l→sg	✓	✓	l→sg	V(:)(S)
	H→ ¬cg		H→ ¬cg	✓	✓	l→sg	H→ ¬cg	H→ ¬cg	H→ ¬cg	V:O
	✓	✓	l→sg	*Con/ CVO	*Con/ CVO	*Con/ CVO	H→ ¬cg	H→ ¬cg	H→ ¬cg	VO
Son or fricative	✓	✓	✓	✓	✓	✓	✓	✓	✓	V(:)(S)
	H→ ¬cg	H→ ¬cg	H→ ¬cg	✓	✓	✓	H→ ¬cg	H→ ¬cg	H→ ¬cg	V:O
	✓	✓	✓	*Con/ CVO	*Con/ CVO	*Con/ CVO	H→ ¬cg		H→ ¬cg	VO

Table 12. Constraints Causing Co-occurrence Restrictions in Kam

The two shaded cells with no constraints listed are discussed in the following section.

3.4.3.8 Maximum perceptibility

In the previous sections, I have accounted for most of the restrictions on tone distribution in Kam. However, two gaps remain in the analysis. First, tone [33] cannot occur on CVO syllables. This is unexpected, since, although it is high register, as a level tone, it should be permitted to surface with a tone span that includes only one mora. Second, tone [11] cannot occur on CV:O syllables. This, too, is unexpected, since this tone is permitted on CVO syllables and it is not a high register tone. Neither of these follows from the consonant-tone interaction system derived above. However, since these tones are part of the tone system, I make a brief proposal here regarding the underlying cause of the restrictions on their distribution.

In particular, I suggest that both of these restrictions may follow from perceptually motivated constraints on the tone system, ultimately rooted in Dispersion Theory (Lindblom 1986, Flemming 1995). First, setting aside tone [35], the tones occurring in CVO syllables are maximally distinct from one another: [55] and [11]. Since these vowels are short, this maximal distinction aids the listener in perceiving the difference. Consequently, tone [33] is excluded. This is similar to the Crosswhite's explanation for vowel systems that exclude mid vowels from unstressed positions (Crosswhite, 2004); although she focuses on stress, she notes that the constraint blocking these vowels crucially seems to apply in those languages where stressed vowels are longer than unstressed vowels.

Second, in CV:O syllables, three low register tones occur, all of which are contour tones: [13], [31], and [323]. A difference between a falling tone and a rising tone is more easily perceptible than a difference between several level tones. I propose that the sonorant portion of these syllables is long enough to carry a contour tone but too short to reliably distinguish a contour tone from a level tone since level tones often involve a non-level portion as the F0 moves towards the target (Y. Xu & Liu, 2006). Thus, the level tone [11] is blocked in this environment. However, both of these ideas require further phonetic investigation.

3.4.3.9 Implications for Tonal Theory

I have argued in this section that the complex phonotactic system in Kam can be explained with the same type of constraints that were used to explain tone blocking in Bade. Specifically, the Kam phonology uses constraints involving the laryngeal features [constricted glottis] and [spread glottis]; there is no voicing in Kam and no reason to assume that these features can somehow be reduced to the feature [voice] (Bradshaw, 1999; Odden, 2002). If they were, this would actually imply that [constricted glottis] and [spread glottis] are ultimately the same feature, since both relate to low tone in Kam and therefore would be reduced to [+voice]. This is clearly an undesirable conclusion since these features are contrastive in many languages.

The analysis in this section also helps to clarify the relationship between register and contour tones. Both are able to interact with consonants, and although Kam register tones interact with [constricted glottis] and contour tones with [spread glottis], this specific correlation does not hold cross-linguistically; the majority of the languages included in the survey do not distinguish between contour and register. Rather, it seems that register and contour tones are able to interact with consonants in the same way. Thus, either the High register tone and the high contour tone share a single feature—high, interpreted as a high target within a specific space—or the consonant-tone interactions are identical because the two distinct high features share an acoustic similarity.

In either case, register tones and contour tones are structurally distinct from one another, and the grammar clearly treats them as independent entities. In Kam, for example, faithfulness to contour alignment is ranked higher than faithfulness to register alignment. Moreover, while they are both able to interact with consonants, they do so independently: low register has no relationship with [spread glottis] and high contour has no relationship with [constricted glottis] in the language. Thus, the relationship between register tone, contour tone, and consonants remains a complex one.

Finally, the analysis in this section shows that tone spans can be aligned to both obstruents and syllable onsets. It also shows that consonant-tone interaction can be sensitive to syllable position, and that as a result, constraints on consonant-tone interaction may need to be structure specific.

3.5 Other types of consonants

So far, this chapter has provided an in-depth look at consonant tone interaction in two languages. However, these represent only a portion of the patterns described in Chapter 2. In this section, I deal more specifically with the cross-linguistic variation, first contrasting the behavior of implosives in three languages and then discussing the other patterns more generally.

3.5.1 A Cross-Linguistic View of Implosives

Implosives, though typically neutral with regard to consonant-tone interaction as seen in Bade, are capable of interacting with both high and low tone. This sort of cross-linguistic variation, while somewhat surprising, seems typical of certain types of consonants. Here, I show that, at least for implosives, this inconsistent behavior is actually predicted by the phonology.

The survey in Chapter 2 lists implosives as having an affinity for low tone in two languages and an affinity for high tone in three. However, by far the most frequent pattern occurs in other languages where consonants interact with tone: implosives are neutral with regard to consonant-tone interaction in at least 19 languages included in the survey. The fact that the neutral pattern is dominant may reflect the fact that implosives do not contrast for [voice] in any of the languages included in the survey—such languages are rare, and none are reported to have consonant-tone interaction.

Given a rich enough phonological system, however, even a universal constraint set predicts divergent behavior across languages. In this section, I demonstrate that, if an implosive has the feature specification [+voice, +constricted glottis], as has often been assumed, then its phonological behavior simply reflects this specification. In particular, since the implosive is specified for two laryngeal features, then both features can also interact with tone. Since an independent realization of these features may, in fact, have opposite effects on F0, this results in seemingly contradictory behavior. I contextualize this idea with data from three Chadic languages, Bade, Ngizim, and Kotoko.

3.5.1.1 Bade: Neutral implosives (Schuh, 2002)

The Bade system was already illustrated in some detail in 3.3. Implosives do not block tone spreading in Bade, even though both voiced and voiceless non-implosive obstruents do interact with tone. Bade has two tones, high and low, both of which spread rightward. Voiced non-implosive obstruents block high tone spreading, while voiceless obstruents block low tone spreading. I repeat the basic data here.

High tone spreads across multiple syllables, as seen in (102) below.

102. a. /nə́ tə̀nkə̀kú/ > nə́ tə́nkə́kú 'I pressed'
b. /nə́ ɗùwàɬú/ > nə́ ɗúwáɬú 'I got tired'
c. /nə́ mə̀skə̀tú/ > nə́ mə́skə́tú 'I turned'

However, modally voiced obstruents block high tone spreading, as shown in (103). Spreading is blocked specifically by the voiced [b] in both (103a) and (103b).

103. a. /nə́ bàzàrtú/ > nə́ **b**àzàrtú (not *b**á**z**á**rtú) 'I shamed'
b. /nə́ tə̀mbə̀lú/ > nə́ tə́m**b**ə̀lú (not *tə́mb**ə́**lú) 'I pushed'

The low tone spreading pattern is somewhat different from the high spreading; low spreads one syllable, but only when it is triggered by a following high tone. Examples are found in (104).

104. a. /dʒə̀.ɗgə́ kó:rón/ > dʒə̀.ɗgə̀ kó:rón 'we followed a donkey'
b. /dʒə̀ kə̀rə́ kó:rón/ > dʒə̀ kə̀rə̀ kó:rón 'we stole a donkey'
c. /dʒə̀ tàɗə́ kó:rón/ > dʒə̀ tàɗə̀ kó:rón 'we released a donkey'

Low tone spreads through voiced obstruents, such as the [g] in (3a); however, voiceless obstruents block low tone spreading, as seen in (105). More specifically, the voiceless [ps] sequence in (105a) and the voiceless [f] in (105b) cause the tone pattern to surface faithfully.

105. a. /dʒə̀ də̀psə́ kó:rón/ > dʒə̀ də̀**ps**ə́ kó:rón (not *də̀psə̀) 'we hid a donkey'
b. /dʒə̀ gàfá kó:rón/ > dʒə̀ gà**f**á kó:rón (not *gàf**à**) 'we caught a donkey'

Implosives behave like sonorants with respect to tone blocking in Bade. Both are neutral, permitting both high and low to spread across them. (106a,b) show high tone spreading across an implosive and a sonorant, respectively, while (106c,d) show low tone doing so.

106. (Repeated from (1) and (3) above)
a. /nə́ ɗùwàɬú/ > nə́ **ɗúw**áɬú 'I got tired'
b. /nə́ mə̀skə̀tú/ > nə́ **m**ə́skə́tú 'I turned'
c. /dʒə̀ tàɗə́ kó:rón/ > dʒə̀ tà**ɗ**ə̀ kó:rón 'we released a donkey'
d. /dʒə̀ kə̀rə́ kó:rón/ > dʒə̀ kə̀**r**ə̀ kó:rón 'we stole a donkey'

I assumed in section 3.2 that implosives were underspecified for voice in Bade. While this provided a neater analysis, it is not actually necessary, so long as voicing is binary, as will be seen in this section. However, if implosives and sonorants are specified for [voice] in Bade, then the constraint H→¬[+vce] would need to be revised to H→¬[+vce, -son, -cg].

3.5.1.2 Ngizim: Implosives show an affinity for H (Peng, 1992; Schuh, 2002)

Ngizim is closely related to Bade, and the two languages are quite similar in their phonology. Ngizim also has two tones, high and low, both of which spread, and voiced and voiceless obstruents block high and low tone spreading respectively, while sonorants remain neutral. However, unlike in Bade, implosives are not neutral with regard to tone spreading; rather, they block low tone spreading. The data are summarized in this section; more detailed accounts can be found in Schuh (1971; 2002) and Peng (1992).

High tone spreads one mora in Ngizim; the examples in (107) show the high tone spreading across voiceless [k], sonorant [m], and implosive [ɓ].

107. a. /ná kàtáú/ > ná kátáú 'I returned'
b. /ná màsú/ > ná mású 'I bought'
c. /ná ɓə̀dú/ > ná **ɓ**ə́dú 'I pinched'

Modally voiced obstruents block high tone spreading, however, as seen in (108), where the high tone fails to spread across voiced [dʒ] or [z].

108. a. /ná dʒə̀bú/ > ná **dʒ**ə̀bú 'I caught'
b. /ná zàdáú/ > ná **z**àdáú 'I arrived'

Low tone spreads one syllable, when triggered by following H, as shown in (109).

109. a. /gàrú báî/ > gàrə̀ báî 'not a wall'
b. /də̀vú báî/ > də̀və̀ báî 'not a road'
c. /mùgbá báî/ > mùgbà báî 'not a gray monitor'

However, voiceless obstruents and implosives both block low tone spreading. In (110a), the voiceless [t] blocks low tone spreading, and in (b), the implosive [ɗ] does the same.

110. a. /cì:tá báî/ > cì:tá báî 'not pepper'
b. /àùɗú báî/ > àùɗú báî 'not a knife'

3.5.1.3 Kotoko: Implosives show an affinity for L (Odden, 2002)

Tone in Kotoko, and its interaction with consonants, differs significantly from the patterns described above. Kotoko has three tones, high, mid, and low, and the initial consonant of a verb stem affects the morphologically determined verbal tone pattern. Odden (2002) shows that modally voiced consonants lower tone and that implosives pattern with the voiced obstruents to lower tone, even though they raise F0 in Kotoko.

Odden's analysis focuses on the Kotoko verb system since verb tense is marked, in part, by the tone on the verb stem. In a low tone verb tense, the stem tone is low for all types of initial consonants, as seen in (10).

111. Infinitive: Underlying L

sàb-à	'grow'
bə̀l-à	'flow'
ɗə̀h-à	'write'

In a high tone verb tense, the stem tone is high following a voiceless obstruent or an implosive but mid following other sounds, as shown by the data in (112). The mid tone is transcribed with no accent mark.

112. Future Tense: Underlying H

n-sáp-à	'chase'	*vs.*	n-zagl-à	'carry'
m-páy-à	'bury'		n-gəɓ-à	'answer'
n-ɗə́v-à	'put'		n-law-à	'fight'
m-ɓál-à	'dance'		n-mar-à	'die'

In a mid tone verb tense, on the other hand, the stem tone is mid following voiceless obstruents and low following all other sounds, including implosives. The verb stems in (113) are repeated from (112), but here the implosives lower mid tone to low, thereby demonstrating an affinity for low tone.

113. Recent Past Tense: Underlying M

sap-ə́m	'chase'	*vs.*	zə̀gl-ə́m	'carry'
pay-ə́m	'bury'		gə̀ɓ-ə́m	'answer'
			màr-ə́m	'die'
			ɗə̀v-ə́m	'put'
			ɓàl-ə́m	'dance'

Odden attributes both of these patterns to the lowering effect of [voice]. In his analysis, implosives are underlyingly unspecified for the privative feature [voice]. They become specified for [voice] midway through the derivation, after high tone is lowered to mid, as in (112), but before mid tone is lowered to low, as in (113).

Such an analysis cannot be translated directly into OT, which is used in this paper to explore typological predictions. Consequently, because of Richness of the Base considerations in OT, the most direct analysis of these data is that implosives show an affinity for both high tone (112) and low tone (113) in Kotoko. I will return to this idea of dual behavior within a single grammar in Section 3.5.1.6, focusing for now on the idea that implosives show an affinity for low tone in Kotoko.

3.5.1.5 Analysis

In order to focus on the consonant-tone interaction itself, I now examine an abstracted set of data that is based on the essential relationships between consonants and tones found in the languages in Sections 1.2-1.4. In this section, I consider three hypothetical languages, each of which have two tones. Both tones spread to the right, with voiceless stops blocking low tone spreading and voiced stops blocking high tone spreading. Implosives have an affinity for high tone in the Ngizim-type language, blocking low tone spreading but permitting high tone spreading. They have an affinity for low in the Kotoko-type language, blocking high tone spreading but permitting low tone spreading. Finally, they display no tone affinity in the Bade-type language, permitting all tones to spread.

Input		**Pseudo-Bade**	**Pseudo-Ngizim**	**Pseudo-Kotoko**
H	á-bà	**á-bà**	**á-bà**	**á-bà**
	á-pà	á-pá	á-pá	á-pá
	á-mà	á-má	á-má	á-má
	á-ɓà	*á-ɓá*	*á-ɓá*	***á-ɓà***
L	à-bá	à-bà	à-bà	à-bà
	à-pá	**à-pá**	**à-pá**	**à-pá**
	à-má	à-mà	à-mà	à-mà
	à-ɓá	*à-ɓà*	***à-ɓá***	*à-ɓà*
[ɓ] is like		[m]	[p]	[b]
Blocking		Nothing	L	H
Permitting		L and H	H	L

Table 13. Implosive Data Summary

Table 13 summarizes the data that this I account for here. Throughout this section, bold font designates words where consonants block tone spreading, while italic font designates words containing implosives.

If implosives have the feature specification [+vce, +cg], then it is straightforward to derive the data in Table 13 using four constraints on combinations of laryngeal features and tones. L→¬[-vce] and H→¬[+vce] are repeated from Section 3.3.5; the new constraints are given in (114) and (115) below.

114. H→¬[+vce,-cg]: Incurs one violation for each segment in a high tone span that has the features [+vce] and [-cg] associated to it.

115. L→¬[+cg]: Incurs one violation for each [+cg] feature associated to a segment in a low tone span.

Finally, the analysis requires constraints that address tone spreading and blocking, given in (18-19). Since the exact mechanism of spreading is unimportant to this paper, I simply use ALIGN as defined in (116); real data, being more than two syllables long, would require a somewhat different definition. MAXT is also repeated from Section 3.3.5.

116. ALIGN-RT: Incurs one violation for each tone that is not aligned to the right edge of the phrase.

I now turn to the derivation of the patterns listed in Table 13. For simplicity, I consider only disyllabic inputs with tone patterns HL or LH. Moreover, I limit candidates to pairs where the first is faithful to the input (violating ALIGN-RT) and the second shows spreading (violating MAXT).

The grammars needed to derive Table 13 all have spreading wherever possible, so ALIGN-RT must be ranked above MAXT in each of the languages in question. Moreover, [p] and [b] always block spreading, so L→¬[-vce] and *H/[+vce,-cg] are ranked above ALIGN-RT.

This basic ranking results in a Bade-like language. The tableaux for each pair are presented in one combined tableau, given in (117). Again, winning candidates where tone is blocked are in bold, and winning candidates containing implosives are in italics.

117.

Pseudo-Bade	L→ ¬[-vce]	H→ ¬[+vce,-cg]	ALIGN-RT	H→ ¬[+vce]	L→ ¬[+cg]	MAXT
a. ☞ **[á]-b[à]**			*			
[á-bá]		*!		*		*
b. [á]-p[à]			*!			
☞ [á-pá]						*
c. [á]-ɓ[à]			*!			
☞ *[á-ɓá]*				*		*
d. [à]-b[á]			*!			
☞ [à-bà]						*
e. ☞ **[à]-p[á]**			*			
[à-pà]	*!					*
f. [à]-ɓ[á]			*!			
☞ *[à-ɓà]*					*	*

In (117b), the high tone spreads over the intervening voiceless [p]; there are no constraints against a voiceless consonant occurring in a high tone span, so the basic ranking ALIGN-RT >> MAXT results in spreading. In contrast, in (117a), tone spreading is blocked because the candidate with spread tone, [á-bá], has a voiced [b] within the span of the high tone. This incurs one violation of *H/[+vce,-cg], since [b] is [+vce, -cg]. Since *H/[+vce,-cg] >> ALIGN-RT, spreading is blocked, and the faithful candidate surfaces. This type of reasoning applies to all candidate pairs in question. Neither of the constraints that implosives can violate are ranked above ALIGN-RT for Bade. Consequently, implosives are neutral with regard to tone spreading in this grammar.

However, if the ranking above is modified so that H→¬[+vce] >> ALIGN-RT, this results in a system corresponding to Odden's interpretation of the Kotoko data. Because [ɓ] and [b] are both [+voice], this constraint ranking causes [ɓ] to behave like

[b], with both blocking high tone spreading. The tableaux are given in (118), with (a) and (c) showing the relevant results.

118.

Pseudo-Kotoko	L→¬[-vce]	H→¬[+vce]	*H/[+vce,-cg]	ALIGN-RT	*L/[+cg]	MAXT
a. ☞ [á]-b[à]				*		
[á-bá]		*!	*			*
b. [á]-p[à]				*!		
☞ [á-pá]						*
c. ☞ *[á]-ɓ[à]*				*		
[á-ɓá]		*!				*
d. [à]-b[á]				*!		
☞ [à-bà]						*
e. ☞ [à]-p[á]				*		
[à-pà]	*!					*
f. [à]-ɓ[á]				*!		
☞ *[à-ɓà]*					*	*

Finally, if *L/[+cg] is promoted instead of H→¬[+vce], the result is a system like Ngizim, where implosives block low tone spreading, as shown in (119). In the candidate pairs in (119e-f), [ɓ] behaves like [p], not because these phonemes share a feature, but because the two relevant constraints, violated by [-vce] in a low tone span and by [+cg] in a low tone span, are both ranked above ALIGN-RT.

119.

Pseudo-Ngizim	L→ ¬[-vce]	*L/[+cg]	*H/ [+vce,-cg]	ALIGN-RT	H→ ¬[+vce]	MAXT
a. ☞ [á]-b[à]				*		
[á-bá]			*!		*	*
b. [á]-p[à]				*!		
☞ [á-pá]						*
c. [á]-ɓ[à]				*!		
☞ *[á-ɓá]*					*	*
d. [à]-b[á]				*!		
☞ [à-bà]						*
e. ☞ [à]-p[á]				*		
[à-pà]	*!					*
f. ☞ *[à]-ɓ[á]*				*		
[à-ɓà]		*!				*

3.5.1.6 Predictions and Discussion

Thus, it is possible to account for the variable behavior of implosives using four constraints on combinations of laryngeal features and tone. In this section, I consider the implications of such an analysis.

When factorial typology is applied to the set of constraints used in Section 3.5.1.5, 13 different grammars are predicted. The previous section relates three of these to known languages. Of the other ten, several are clearly attested in the literature. Two of these ten predicted grammars are quite common: languages with no tone spreading (i.e. languages with MAXT ranked highest), and languages with no tone blocking (i.e. languages with ALIGN-RT ranked highest).

A third ranking results in a grammar that is similar to the actual Kotoko system; it is not clear that the Pseudo-Kotoko system is represented in the survey . In particular, if all four laryngeal constraints are ranked above ALIGN-RT, this results in a grammar where an implosive can block both high and low tone spreading in the same language, as shown in (120). Such a grammar is permitted since two constraints refer to [ɓ]; one of these results in high tone blocking, as in (120c), and the other in low tone blocking, in (120d). The fact that such a grammar can be generated is a considerable benefit for this constraint system; it will be seen below that a less rich phonology cannot produce this result.

120.

Kotoko-type language	L→¬[-vce]	*L/[+cg]	H→¬[+vce]	*H/[+vce,-cg]	ALIGN-RT	MAXT
a. ☞ [á]-b[à]					*	
[á-bá]			*!	*		*
b. [á]-p[à]					*!	
☞ [á-pá]						*
c. ☞ *[á]-ɓ[à]*					*	
[á-ɓá]			*!			*
d. [à]-b[á]					*!	
☞ [à-bà]						*
e. ☞ [à]-p[á]					*	
[à-pà]	*!					*
f. ☞ *[à]-ɓ[á]*					*	
[à-ɓà]		*!				*

Finally, the constraint set proposed in this paper predicts that [p], [b], and [ɓ] will behave independently with regard to tone interaction, with one exception: [ɓ] cannot show an affinity for low tone unless [b] also does. The summary in (121) shows that some, but not all, of the seven remaining predicted grammars are attested.

121. Known interactions of voicing and implosives with tone; ~ indicates an affinity
    a. [b] ~ L only: Many languages (Bradshaw, 1999)
    b. [p] ~ H only: Limburgian (Hermans & van Oostendorp, 2000)[51]
    c. [ɓ] ~ H only: None known; the constraint refers specifically to [cg], which is attested in a number of languages (see Table 2).
    d. [b] and [ɓ] ~ L: Xhosa (Jessen & Roux, 2002)
    e. [b] ~ L, [ɓ] ~ H: None known
    f. [p] ~ H, [ɓ] ~ H: None known
    g. [b] and [ɓ] ~ L, [ɓ] H: None known

The question, then, is whether the missing languages are real or accidental gaps in the typology. It is entirely possible that they are accidental, since much of consonant-tone interaction takes place in languages that are only minimally described, and implosives are relatively rare. Also, as already indicated in Section 3.3.8.2, a more simplified assumption about feature specification cannot account for the full set of data.

The analysis presented here has implications for all consonants that are [+cg], not just implosives. In particular, it implies that [-vce, +cg] sounds should not show an affinity for low tone, since implosives are claimed to lower tone by virtue of their [+vce] specification. However, the behavior of non-implosive [+cg] consonants varies significantly from language to language. I address this variability in the following section.

3.5.2 General consonant types and tone

I now turn to a broader examination of consonant types included in the survey in Chapter 2. The table below provides a summary of the cross-linguistic possibilities found in the survey.

[51] This may, however, be only historical (Boersma, 2006).

	Affinity for L	*Affinity for H*
Voiced obstruent	√	
Voiceless obstruent		√
Implosive	√	√
Sonorant	√	√
Voiceless aspiration, voiceless fricative, /h/[52]	√	√
Glottal/ Glottalized (nonimplosive)	√	√
Stiff/Tense		√
Slack/Lax	√	

Table 14. Types of Consonant-Tone Interaction

I tentatively omit one category from Table 14 that is represented by only one language in the survey, but I address it briefly here. Limited data is available in Carrier, the only language found where plain voiceless stops show an affinity for low tone. It is possible that, since Carrier is a language that connects aspiration to high, Carrier speakers phonologize the [+spread glottis] > [-spread glottis] pattern into a phonological constraint that associates [-spread glottis] with low.

I follow Bradshaw (1999) in suggesting that the connection between sonorant and low is via the feature [voice]—in particular, that in Wujiang, sonorants are specified for [voice] and pattern with the voiced obstruents. However, sonorants also pattern with high tone in three languages. In these languages, Bassa, Sayanci, Musey, sonorants also pattern with implosives and voiceless obstruents. The Bassa pattern is actually somewhat peculiar in that consonants interact only with contour tones, not level tones. Also, it should be noted that the sonorant interaction can only be considered an interaction with high if this three-tone system can reasonably be divided into contour and register, since the falling tone with which the sonorant interacts in

[52] This includes only those languages where these segments do not pattern with voiceless obstruents as expected. A language like Bade, where it is clear that the relevant contrast is between voiced and voiceless stops, is categorized with the voiceless obstruent group even though these obstruents are aspirated.

Bassa is mid-low; in a register system, this is low register, high-low contour. However, barring further evidence, the Bassa data might be better addressed as a three tone system where mid tone is neutral and there are constraints the consonants with an affinity for low tone, e.g. [vce]→L and L→[vce]. This effectively blocks other sounds from appearing with low tone and blocks voiced obstruents from appearing with mid tone. Assuming a general constraint blocking high-low tones, this derives the requisite pattern. The Sayanci data are more complex; it seems plausible to apply this type of solution, but again, a careful analysis of the data is necessary to verify that this is, in fact, tenable.

The Musey data appear to operate in a limited part of the lexicon, and Shryock's (n.d.) manuscript is unclear about whether it is possible to formulate a similar analysis. If this type of analysis proves to be untenable, the other alternative is that the feature [sonorant], or some other feature of sonorants, is able to show an affinity for high tone.

Among the other consonants, it is trivial to account for the tense/lax connection to tone, since both have a phonetic realization that directly affects F0, and although the data are limited, the available data indicate a consistent connection between lax and low, tense and high.

However, the other consonant types are more challenging. In the previous section, I suggested that implosives could achieve their dualistic behavior by being specified both [+voice] and [+constricted glottis]. However, all glottal or glottalized consonants, with the possible exception of ejectives, show this pattern, and there is at least one language in the survey where glottal stops show a connection to both low and high tone. The same type of dualistic behavior is found for aspirated consonants and fricatives, although I have no examples of languages where these have an affinity for both high and low.

There are two basic approaches that can be taken here. One is that the high patterning sounds are phonetically and phonologically different than the low patterning sounds. Under this view, too few features are assigned to the larynx, and more are needed to properly express the wide variety of laryngeal articulations that are possible. While this may certainly be the case, this approach is not sufficient to account for the data at hand. For example, in Kam, there is a phonological affinity between [+constricted glottis] and low register. Under a split-feature analysis, this means that Kam should have the creaky-type glottalized segments that cause a phonetic F0 lowering. However, the syllable-final glottalized segments actually raise F0 in Kam (Edmondson, 1992), and at least for my consultant, can cause the vowel to sound tense.

The other possibility, then, is that multiple natural phonetic relationships can exist between a laryngeal feature and a tone feature. This approach has been carefully documented for the historical case of tonogenesis in Athabaskan languages (Kingston, 2005). Here, Kingston argues that the same feature, [constricted glottis], can result in both high and low tone depending on the timing of the glottal gesture. Section 3.2.6 showed that both aspiration and glottalization can either raise or lower F0. While some of the phonetic differences may actually result from differences in experimental methodology, at least one of the studies discussed there shows different results among speakers who all completed the same experimental task. Under this view, then, [constricted glottis] and [spread glottis] can show a natural affinity for both low and high tone.

However, the question remains as to how a speaker of a language like Kam can select a constraint that is phonetically natural according to articulatory and cross-linguistic studies of naturalness, but phonetically unnatural according to the phonetics of the language. Again, there are several possibilities. The first is that the child learning Kam is able to acquire this constraint through an innate knowledge of universal grammar. The second is that there is actual phonetic variability in Kam, but that the small number of speakers who have been recorded do not reflect this variability. In this scenario, the learner is able to support both L→[cg] and H→[cg] based on the phonetic patterns that she hears, but she will ultimately discard H→[cg] because it does not match the phonological patterns of the language. Finally, it is possible that the phonetic basis of the constraints is learned in the babbling stage, and once the abstract constraints are formed, the language learner is able to apply them appropriately to the phonological data she encounters.

Under any view of the relationship between phonetics and phonology, however, it is necessary that the same phonetics be able to generate multiple constraints. For example, Kam also showed that [sg]→L and L→[sg] are both necessary to the grammar. While there is a phonetic basis for an affinity between [+spread glottis] and low tone, this does not dictate which logical relationship will be expressed by the constraint. The phonology of each language must be examined to know exactly which constraints are used in it.

Finally, the diversity of consonant types that interact with tone indicates that it is impossible to merge laryngeal and tone features. If, for example, [+voice] and low tone are merged into a single feature [+voice/L] because of their potential for phonological interaction (Bradshaw, 1999; Odden, 2002), then by the same reasoning, [-tense], [+constricted glottis], and [+spread glottis], should also be merged into this feature. This is implausible since languages such as Bengali are able to contrast, for example, voiced obstruents and breathy voiced obstruents. Moreover, pairs of constraints like L→[cg] and H→[cg] add to the evidence that tone and consonant features should not be merged; under an extreme version of this theory, both laryngeal and tone contrasts will disappear.

3.6 Summary

This chapter discussed the phonology of consonant-tone interaction from various perspectives. In the end, there are several important conclusions to be drawn. First, the phonology explored in this chapter also increases our understanding of what type of phonology is necessary to account for consonant-tone interaction. A representational account (such as feature spreading) cannot account for this interaction because such an account collapses tone and consonant features into a single feature. However, I showed that it is not only necessary to maintain a much larger number of distinctions among laryngeal features than among tone features, but also that if opposite affinities are demonstrated by the same feature, this would cause the feature contrast to collapse completely.

Instead, I argue that consonant-tone interaction relies on constraints that relate two sounds that are articulatorily or perceptually similar but do not share features. More specifically, glottal features and tone share a common articulator in the larynx; moreover, this articulatory relationship may be increased in order to enhance the perceptibility of a consonant contrast. Consonants and tones are connected via a tone span, which marks the segmental domain of the tone; framing the analyses in this context contributes to the understanding of span theory. Constraints on consonants and tones can be quite specific, including a domain in which the constraint applies.

To this end, the phonology of each language must be examined to know exactly which constraints are used in it and to ensure that an analysis can be made consistently within the larger phonology of the language. For example, the constraint H→¬[-vce] is active in Bade, but it is likely not to be active in a language like Wujiang where voiceless unaspirated consonants contrast with voiceless aspirated consonants. Here, we would expect instead that the consonant-tone constraints would refer to [spread glottis].

Finally, it is seen that there is no apparent distinction between contour and register tones in terms of their interaction with consonantal features. I take this as evidence that, while contour and register differ structurally, there is no specific structural plane on which consonant-tone interaction occurs (cf. Yip, 1995, Bao, 1999)

Chapter 4 Phonetic Modeling

This chapter explores phonetic aspects of consonant-tone interaction in Bade. In it, I discuss two primary models of F0 movement in Bade. One models the median F0 value of a vowel, while the second models F0 measurements made at specific points in time in vowels and sonorants. The main purpose in creating these models is to answer two questions regarding consonant-tone interaction in Bade. The first of these is how consonants affect F0 in Bade, and whether this fits with general cross-linguistic patterns, or whether the unique tone patterns of Bade are related to a unique set of consonant effects. The second is whether there is a phonetic basis for the tone span posited for Bade in Chapter 3. The models show that preceding consonants and spans have a statistically significant but complex effect on F0 in Bade.

This chapter is also of methodological interest in that it builds these models from an unbalanced set of data collected during phonological field work sessions. As is the case with many understudied languages, little recorded data is available, and there are numerous obstacles to conducting controlled experiments with large numbers of Bade speakers. Even when recorded data is available, it is often judged to be insufficient for phonetic studies, since the traditional statistical techniques employed in these studies require balanced experimental designs with equal numbers of measurements for each possible combination of effects. However, the models used here, linear mixed effect models, are robust even under unbalanced conditions.[53] These models permit not only fixed effects, such as those typically controlled in an experiment, but also random effects, such as the effect of an individual speaker or

[53] The statistical methods used in this chapter are primarily based on Baayen's application of mixed models to linguistic data (Baayen, 2004, In press).

utterance. Because these models account for the fact that speakers are drawn at random from a larger population, they are considered extendable to that population. An additional benefit of these models is that it is possible to include a large number of effects in the model, including interactions between effects. In some sense, the model isolates each effect and determines whether, and to what extent, it contributes to the measured result. To my knowledge, only one other language has tone modeled in this way (Evans, Chu, & Aston, 2008).

4.1 Data

The data in this section are compiled from two different periods of data collection. In both cases, the data were collected in field session with Bade speakers in Nigeria by Dr. Russell Schuh, who also transcribed the sessions. The details regarding this recording are provided below.

In the first of these sessions, on May 24, 1975, Muza Gana Amshi, a 25-30 year-old civil servant from Amshi, Yobe State, Nigeria, was recorded. The recording took place in the Gashua Local Authority Reading Room, Gashua, Yobe State, Nigeria. The data was originally recorded on a Uher 4000 Report reel-to-reel tape recorder, recorded at 3.75 inches/second with a Uher M514 microphone. The data were digitized in 2007 from the original tapes. The second of these sessions took place in 2007. Two speakers, Gabaju Namaliya Dagona and Bala Wakili Dagona, were recorded. Both speakers are college educated males in their mid-40s who were born in Dagona village, which is located in the central part of the Western Bade dialect area. The speakers were prompted in Hausa, resulting in slight differences in choice of vocabulary or syntax. In general, each phrase was produced once by Mr. G. Dagona and twice by Mr. B. Dagona in two separate sessions; Mr. G. Dagona was recorded in Gashua, Yobe State, Nigeria, and Mr. B. Dagona in Potiskum, Yobe State, Nigeria. Mr. G. Dagona and Mr. B. Dagona were both recorded using a Marantz PMD 201 monaural audio cassette recorder and a Sony WCS-999 wireless microphone. These files were then digitized as AIFF files using Peak LE 5.2 software on a MacBook Pro computer at 44.1 KHz. Mr. B. Dagona's second session was video recorded with a Sony DCR-TRV70 NTSC camcorder and the same type of wireless microphone as in the other sessions. The resulting video was digitized using Final Cut Express HD and the audio was then copied as an AIFF file using Peak LE 5.2, retaining the 48 KHz sampling rate. In total, this corpus consists of 425 utterances.

Because of background noise, electronic interference, and recording methodology, there is a considerable degree of noise in the signal. Nevertheless, the pitch is clearly discernable and appears to be measured accurately in Praat.

4.1.1 Segmenting

The data were initially segmented using the forced aligner included in OGI Speech Tools (Hosom, 2002). Although the program was not trained on Bade data, it was provided with the expected phonetic transcription (or closest English equivalent) for each utterance, and it produced time-aligned boundaries as output. These proposed boundaries were then checked for accuracy and adjusted in the case that they disagreed with my judgment by more than 5 ms. Because of the noise in the data, vowels were marked conservatively, with onset and offset marked at the point when at least two formants were clearly visible. Tones were typically marked according to whether they were phonologically high or low. However, since the phonological status of falling tones remains somewhat unclear, a tone was labeled as falling if there was a change of more than 15 Hz over the course of the vowel. In addition, each segment was labeled for a variety of factors, including phoneme class, tone span, position in phrase, and sentence structure. This information was stored in a Praat textgrid file.

4.2 Modeling the median

The first model of this data models a single F0 measurement per vowel. I focus here primarily on the median F0 over the duration of the vowel, since this measurement is more robust against outliers than the mean.

4.2.1 Median data

The median F0 measurement used in this model is the value automatically extracted by Praat. To guard against voice quality effects at the edges of a vowel, the first and last 10 ms are excluded for vowels longer than 40 ms. For vowels less than 40 ms, the median value is based on the entire vowel. Excluded from the data analyzed here are any data where the mean or median is undefined, i.e. vowels for which no F0 measurement was possible, and non-edge vowel data where mean or median of the immediately preceding or following vowel is undefined, since the model includes data on tone spreading. The resulting data set contains 2047 points. Figure 6 provides boxplots of these data, subdivided by speaker and tone.

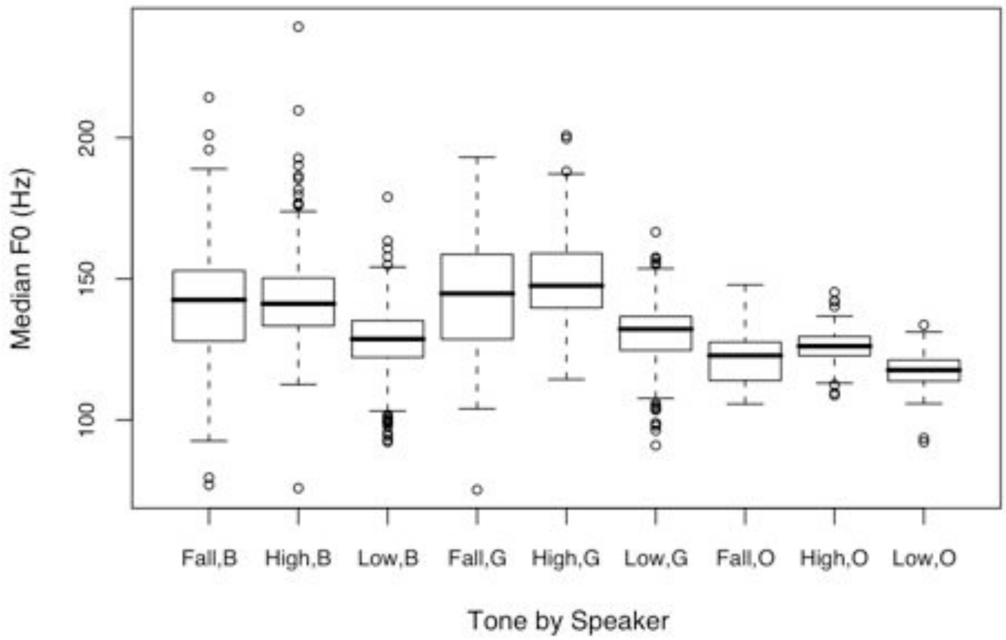


Figure 6.   Median F0 by Tone and Speaker

The boxplot in Figure 6 also provides a general overview of the Bade data. It can be seen that the high and low tones, while distinct, are quite close to one another and overlap considerably in their distribution. Those tones marked as phonetically falling, on the other hand, have median distributions that are quite similar to the high tone, though they are wider ranging. For Mr. B. Dagona (B), the mean high tone value is 143 Hz, while the mean low tone is 128 Hz. Mr. G. Dagona (G) has a similar, though slightly higher range, with the average high tone at 150 Hz and low at 131 Hz. Mr. Amshi (O) has a somewhat lower voice overall, with an average high of 126 Hz and a low of 117 Hz. Since the distribution is so variable, it would be counterproductive to remove outliers based on the overall mean. Nevertheless, since the measurements were automated, it is likely that they include data points representing measurement errors or poor voice quality. Consequently, I eliminated the outliers that fall roughly outside the 95% confidence interval for the median, i.e.

outside the whiskers in the boxplots, resulting in a final data set consisting of 1961 measurements.

4.2.2 Median F0 model

There are many factors that can influence the F0 of a syllable. Of these, I take into account the following:

Factor	**Levels**	**Comments**
Tone	High, Low, Falling	High, Low are lexical tones; Falling factors out phonological or phonetic falls.
cTime	Continuous	Time of vowel midpoint in ms; measured from onset of first vowel in utterance. Values are centered according to the mean measurement across all data.[54]
Duration	Continuous	Duration of vowel.
Preceding Segment	Voiced, Voiceless, Implosive, Sonorant, Vowel, None	Category of preceding segment. If Vowel, indicates some type of deletion has take place. If None, vowel is utterance-initial. These two categories are very rare.
Edge	Yes, No	Accounts for edge effects; value is Yes for vowels from the first and last syllable of the utterance and No for others.
Syllable Type	Open, Closed	Syllable type for syllable.
Span	Same, Different	If preceding vowel is in the same phonological span, as defined in Chapter 3, this has the value Same. Different indicates different span or utterance edge.
Following Span	Same, Different	See Span comments.

Table 15. Factors and Levels in Median F0 Model

All of the effects listed in Table 3 are considered fixed effects. Although Following Segment was also originally considered as well, it was found not to be significant

[54] The value for cTime is centered so that the model does not show a spurious correlation between slope and intercept.

when all other factors were included. These factors are represented in Figure 7 for the utterance də̀mà:n hé:tà.

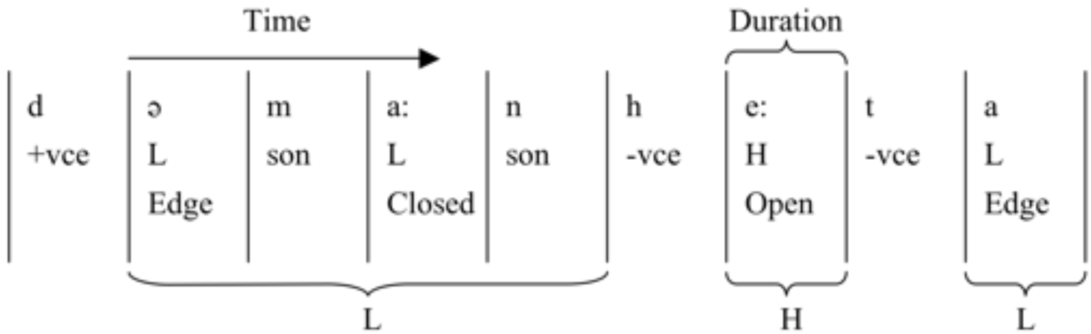


Figure 7. Schematic Labeling of Bade Utterance

In the figure specify the Edge factor only where the value is *yes*, and I provide the value for SyllableType on the other vowels. The span factors are represented only indirectly; the spans themselves are marked by the brackets below the segments. In this case, the low tone has spread across the second syllable of the first word. Thus, for the vowel [ə], the value for Span is *different* and the value for FollowingSpan is *same*, whereas for the vowel [a:], the value for Span is *same* and the value for FollowingSpan is *different*. For the vowels [e:] and [a], both Span and FollowingSpan have the value *different*.

The value of the preceding and following tones are not directly included in this model. If Span has the value *same*, then this indicates that the preceding tone is the same as the tone on the vowel in question. However, if Span has the value *different*, the value of the preceding tone is unknown. In this case, the preceding tone could be different from the current tone, but it could also be undefined, if the vowel is from the first syllable of the utterance, or the same tone, if the vowel is from the last syllable of a noun, or from the last syllable of a verb to which tone has spread, if an obstruent that prevents spreading intervenes, or if the environment for spreading is wrong. This reflects the assumptions made about Bade tone in Sections 3.3.2 - 3.3.4.

The model also includes two individual random effects: Speaker and Utterance. These take into account the fact that idiosyncratic properties of a specific speaker or a specific sentence may affect F0. The model also includes random slopes for Utterance based on a centered Time measurement; this permits the model to take into account different declination rates across utterances. Evaluation via a Markov Chain Monte Carlo (MCMC) sampling indicated that an interaction between slope and intercept for cTime was not significant and that a random slope measurement for Speaker presented difficulties with collinearity; consequently these two random factors were not included in the model. A model including only random effects differs from the null model at a probability of $p < 0.0001$; this is unsurprising since the null model has an R^2 value of 0.002, compared to an R^2 value of 0.546 for the model with only random effects.

The final model for Median F0, including both fixed and random effects, was discovered by creating an initial model including all the interactions between factors that have potential to show a combined effect on F0 and then proceeding to eliminate those that were not significant one level of complexity at a time. Crossed factors resulting in singularities or false convergence were, by necessity, not included. The final model for Median F0 is schematized in (122), with random factors given in brackets. This model has an R^2 value of 0.748, with the random factors accounting for 73.0% of the variance that the total model accounts for.

122. Median_F0 = PrecedingSegment + Edge + Duration x SyllableType
+ Span x Tone + FollowingSpan x Tone
+ cTime x Tone + cTime x FollowingSpan
+ [Utterance] + [Speaker] + [cTime|Utterance]
+ Intercept

Table 16 shows the crossed effects that are significant in the final model and discusses what each crossed effect signifies.

Crossed Effect	Significance
SyllableType x cDuration	The vowel of a closed syllable is shorter in duration than the vowel of an open syllable. Together, this has a minor effect on F0; this likely takes into account the greater declination on a longer vowel and the edge effects included for very short vowels.
Tone x FollowingSpan	The effects of being in the same or different span are modified based on whether the tone is high or low, and vice versa.
Tone x Span	
Tone x cTime	The joint effect of tone and span on F0 is further modified by their position in time. This probably indicates a compression of the pitch range.
FollowingSpan x cTime	The effect of a vowel being in the same span as the following vowel varies with respect to time.

Table 16. Crossed Effects in Median Model

The estimated values for the coefficients were derived using the *lmer* function in the *lme4* package (Bates, 2007) in *R* (R Development Core Team, 2008) and are provided in Table 17. If a crossed effect is included in the model, then each level of that effect and each effect contributing to the crossed effect is, by definition, also included in the model, though in some cases these effects do not reach significance on their own. Effects in the table are significant at $p < 0.05$ for $|t| > 2$. While for large data sets, it is typically the case that $|t| > 2$ indicates a significant interaction, this is not the case for all factors tested for this data set; Appendix 2 discusses this in further detail and lists *p*-values associated with these factors based on an MCMC sample.

	Estimate	Standard Error	|t|
(Intercept)	133.368601	6.261111	21.301
Tone(H)	6.483318	0.828635	7.824
Tone(L)	-6.408741	0.867642	7.386
PrecSegment(none)	-1.716815	4.3652	0.393
PrecSegment(son)	3.488424	0.919801	3.793
PrecSegment(vce)	0.745261	0.948666	0.786
PrecSegment(-vce)	7.233391	0.928507	7.79
PrecSegment(V)	8.319552	4.782556	1.74
cDuration	0.005595	0.016826	0.333
SylType(open)	-3.033227	0.54943	5.521
Edge(yes)	-5.278089	0.508187	10.386
cTime	-0.025958	0.00215	12.071
FolSpan(same)	3.064492	1.00298	3.055
Span(same)	5.91497	0.957918	6.175
cDuration x SylType(open)	-0.053769	0.017703	3.037
Tone(H) x cTime	0.004398	0.002308	1.906
Tone(L) x cTime	0.008172	0.002479	3.296
Tone (H) x FolSpan(same)[55]	-4.111029	1.212429	3.391
Tone(L) x FolSpan(same)	-3.953543	1.406233	2.811
cTime x FolSpan(same)	0.00452	0.001991	2.271
Tone(H) x Span(same)	-3.236668	1.127162	2.872
Tone(L) x Span(same)	-10.615604	1.428555	7.431

Table 17. Coefficients for Fixed Factors in Median F0 Model

In particular, both Span and FollowingSpan are significant contributors to the Median F0 model. However, the amount of contribution varies depending on the other factors involved; I return to this idea shortly. PrecedingSegment also contributes significantly to the model; this is somewhat surprising, given that the median values are used. Moreover, this is not a duration effect, as one might expect, where F0 fails to reach its target in short vowels; although the interaction cDuration x PrecedingSegment was tested, it did not reach significance.

[55] Rerunning the model with low tone withheld indicates that Tone x FollowingSpan is is not significantly different for high and low tones; this is also true for Tone x cTime. Tone x Span shows a significant difference between high and low tones.

The values in this model abstract away from the random factors; for this reason, it is considered statistically valid for the general population rather than just the population tested. This means that the same factors are predicted to be significant if a new Bade speaker is tested, but if that speaker's mean F0 value is actually 150 Hz, then 16.6 Hz (150 - 133.4) will need to be added to the model prediction order to arrive at a predicted value for that speaker.

Nevertheless, the relative values in the model are predicted to hold across speakers. Linear mixed models are additive; that is, each level of a factor in the model is associated with a specific coefficient, and these coefficients are added together to find the predicted F0 value. Since the values for cTime and cDuration are centered, a value of 0 for these factors represents a vowel of average length taken from the average utterance midpoint. If levels for the other factors are chosen at random, we can arrive at a predicted F0 value for a vowel with these properties. For example, if the preceding segment is voiceless, the vowel has High tone, the vowel comes from an open syllable, and it is in the same span as the previous vowel but a different span from the following vowel, and it is not at the edge of an utterance, then the predicted value is 146.8 Hz. The procedure for deriving this value is given in (123), with all values taken from Table 17.

123.	Intercept	133.4
	Tone (high)	+ 6.5
	PrecedingSegment (voiceless)	+ 7.2
	cDuration (0)	+ 0
	SylType (open)	- 3.0
	Edge (no)	+ 0
	cTime (0)	+ 0
	FollowingSpan (different)	+ 0
	Span (same)	+ 5.9
	cDuration x SylType (0,open)	+ 0
	Tone x cTime (high,0)	+ 0
	Tone x FolSpan (high,diff)	+ 0
	cTime x FolSpan (0,diff)	+ 0
	Tone x Span (high,same)	- 3.2
	Predicted Value (total)	= 146.8 Hz

This value is independent of Utterance and Speaker. As a check, there are 53 vowels in the data set that meet these qualifications, with cDuration and cTime not taken into account. The mean value of these vowels is 143.3 Hz, with a standard deviation of 14.5. When the mean values of cDuration (-7.3) and cTime (79.5) for the subset vowels are taken into account, the predicted value for such a syllable is 146.8 + -7.3 * 0.006 + -7.3 * -0.05 + 79.5 * -0.03 + 79.5 * 0.004 = 145.1 Hz.

4.2.3 Consonant effects

Given that the basic difference between high and low tone in Bade is roughly 13 Hz, the fact a syllable with an initial voiceless consonant has an F0 value nearly 4 Hz higher than an otherwise identical syllable with a sonorant onset is rather surprising. The withheld level for PrecedingSegment is implosive—thus, a voiceless consonant is predicted to raise the median F0 by 7.2 Hz compared to a syllable with an implosive onset. The levels *voiced* and *implosive* are not significantly different from each other, however, since $p > 0.05$ for the level *voiced*. A simultaneous Tukey test[56] on the coefficient values for PrecedingSegment shows that the pairs (voiced,sonorant), (voiceless, sonorant), (voiceless, voiced), and (voiceless, implosive) are significantly different at $p < 0.001$ and the pair (implosive, sonorant) is significantly different at $p < 0.01$. Thus, for median F0, the model yields the hierarchy in (124).

124. Voiceless > Sonorant > Implosive, Voiced

4.2.4 Span effects

The other factors of especial interest here are Span and FollowingSpan. These show significant interactions with Tone, and for FollowingSpan, cTime also has a significant interaction, indicating that spans behave differently for high and low tones. Since Span is partially predictable based on the value of PrecedingSegment, these factors cannot be crossed in the model. However, their effects can be independently examined. In the following table, I provide these effects for high and low tones. I assume values of 0 for cTime and cDuration, an Edge value of *no*, and a closed syllable. Thus, the combined effect from factors beside Span, Following Span, and PrecedingSegment is simply that of the Intercept plus the *high* value, 139.9, or the Intercept plus the *low* value, 126.9. The two logically impossible combinations in the table, those that require a voiced segment to occur in a high tone span, are marked n/a. The combined effect cells contain the added coefficient values for Span, FollowingSpan, and PrecedingSegment; the predicted value cell adds the combined effect cell value to the combined value given above for other factors.

[56] This test uses the *multcomp* package (Hothorn et al., 2008).

Span	Following Span	Preceding Segment	Combined Effect (H)	Predicted Value(H)	Combined Effect (L)	Predicted Value(L)
Same	Same	Voiced	n/a	n/a	-4.9	122
Same	Same	Voiceless	8.9	148.8	n/a	n/a
Same	Same	Implosive	1.7	141.6	-5.6	121.3
Same	Same	Sonorant	5.2	145.1	-2.1	124.8
Same	Different	Voiced	n/a	n/a	-5.8	121.1
Same	Different	Voiceless	9.9	149.8	n/a	n/a
Same	Different	Implosive	2.7	142.6	-6.5	120.4
Same	Different	Sonorant	6.2	146.1	-3.0	123.9
Different	Same	Voiced	-0.3	139.6	-0.2	126.7
Different	Same	Voiceless	6.2	146.1	6.3	133.2
Different	Same	Implosive	-1.0	138.9	-0.9	126
Different	Same	Sonorant	2.5	142.4	2.7	129.6
Different	Different	Voiced	0.7	140.6	0.7	127.6
Different	Different	Voiceless	7.2	147.1	7.2	134.1
Different	Different	Implosive	0	139.9	0	126.9
Different	Different	Sonorant	3.5	143.4	3.5	130.4

Table 18. Modeled Adjustments for Span, FollowingSpan, and PrecedingSegment

The values in this table show that, although the predicted differences for high and low tone are only 13 Hz apart, this difference is enhanced to more than 20 Hz when the vowel is in the same span as the preceding tone.

The combined adjustments for the four possible combinations of Span and FollowingSpan alone are given in Table 19; the tone values take into account the interaction effects between span and tone. The example column shows one example a CVCVCV sequence resulting in such a measurement, where the predicted value is for the middle V.

Span	FollowingSpan	High	Low	Example
Same	Same	1.7	-5.1	C[VC**V**CV]
Same	Different	2.4	-4.7	C[VC**V**]CV
Different	Same	-1.0	-0.9	CVC[**V**CV]
Different	Different	0	0	CVC[**V**]CV

Table 19. Modeled Effect of Span and FollowingSpan on Median F0

However, when comparing differences between adjacent vowels, the effects of time must also be taken into account. If there is a distance of 250 ms from the midpoint of the preceding vowel to the midpoint of the vowel on which the measurement is made, then there is a predicted independent declination effect of -5.4 Hz (=250 * -0.026 + 250 * 0.004) for high tones and one of -4.4 Hz (=250 * -0.026 + 250 * 0.008) for low tones; this is presumably the effect of downdrift. Because the factor cTime x FollowingSpan is significant, this must also be taken into account; if the following vowel is in the same span, then at 250 ms this modifies the result by an additional effect of 1.1 Hz (=250 * 0.0045). Thus the total predicted change in F0 based on Span, FollowingSpan, and cTime is found in Table 20. This combines the values in Table 19 with the declination effect coefficients given in this paragraph.

Span	FollowingSpan	High	Low	Example
Same	Same	-2.6	-8.4	C[V1CV2CV]
Same	Different	-3.0	-9.1	C[V1CV2]CV
Different	Same	-5.3	-4.2	CV1C[V2CV]
Different	Different	-5.4	-4.4	CV1C[V2]CV

Table 20. Modeled Change Between V1 and V2 with Difference in cTime Value of 250

Taken all together, the information in these tables shows that, if a high tone vowel is in the same span as the preceding vowel, its median F0 value is modeled as declining less than if the vowels are in two different spans. The values are slightly higher if the following vowel is in a different span than if it is in the same span, though if the preceding span is different, the effect is negligible.

On the other hand, low tones show the opposite effect. If a low tone is in a different span from the preceding vowel, it has a higher median value than it would if it were in the same span. The effect of being in the same span as the following vowel, on the other hand, is that the median F0 value is slightly higher than it would be if it were not in the same span, at least if the preceding vowel is in the same span; if the preceding vowel is in a different span, the effect is negligible. Again, this is the opposite of the effect that high tone shows.

One could perhaps view the overall effect of being in the same span as a preceding vowel as enhancing the difference between low and high tones, whereas being in a different span will make the difference in tone height less pronounced. On the other hand, being in a different span from the following vowel enhances the difference, while if a vowel is in the same span as the following one, this difference is less pronounced; however, the effect of the following span is extremely small overall. It should be noted that the differences here cannot be attributed to Edge effects, since the interaction between Edge and Tone was tested and found not to be significant.

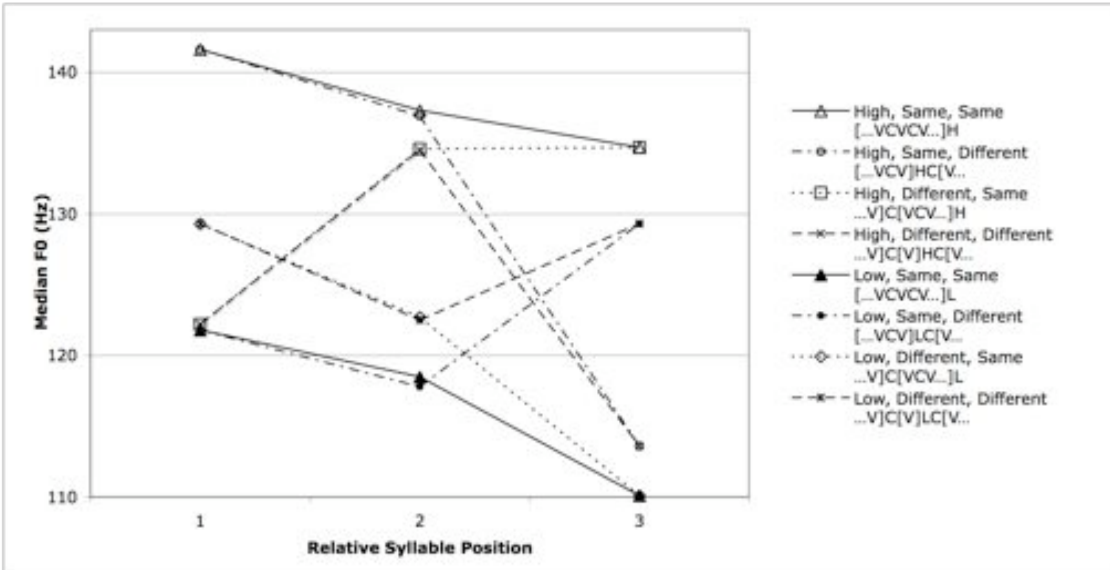


Figure 8. Modeled Values Based on Span, FollowingSpan, and Tone

Figure 8 illustrates the effect of Span, FollowingSpan, and Tone across three syllables with midpoints at cTime 0, 250, and 500 ms. The legend lists the Span and FollowingSpan values for Syllable 2. These values are calculated with the Span value for Syllable 1 set at *same*, and the FollowingSpan value for Syllable 1 matching that of the Span value for syllable 2. Likewise, Syllable 3 has FollowingSpan values of *same* for all conditions, and the Span value matches the FollowingSpan value for Syllable 2.

4.2.5 Modeling with tone instead of span

It is also possible to model these data using PrecedingTone and FollowingTone instead of Span and FollowingSpan. The resulting model is more complex; thus, it is not surprising that it has a slightly higher R^2 value, 0.784, with 69.6% of the data accounted for by random factors. However, since R^2 is sensitive to model complexity, this is not the best way to compare goodness of fit across models. Other criterion, which balance model complexity with correlation, show this model to be comparable to the span model presented in the previous sections: according to the AIC, the tone model is a better fit (tone = 14391, span = 14500), whereas according to the BIC, the span model is a better fit of the data (tone = 14787, span = 14639). The tone model is presented in Table 21, with the results of the MCMC test contained in Table 28 in Appendix 2.

Table 21. Coefficients for Fixed Factors in Median F0 Model Using FollowingTone and PrecedingTone

	Estimate	**Std. Error**	**t value**
(Intercept)	123.0000	6.2230	19.77
PrecSegment(implosive)	-0.9087	1.8410	0.494
PrecSegment(none)	5.5870	11.5600	0.483
PrecSegment(voiced)	-0.7550	1.0300	0.733
PrecSegment(voiceless)	2.9060	1.5240	1.907
PrecSegment(vowel)	10.9600	10.1900	1.076
cDur	-0.0234	0.0141	1.661
FollSegment(implosive)	0.6324	1.2890	0.491
FollSegment(none)	2.0320	1.7170	1.183
FollSegment(voiced)	-0.7600	0.7846	0.969
FollSegment(voiceless)	-2.3500	0.6255	3.756
FollSegment(vowel)	-1.0680	2.2710	0.47
cTime	-0.0089	0.0044	2.033
SyllType(open)	-1.8350	0.6511	2.818
FollTone(F)	4.3670	1.2650	3.452
FollTone(H)	2.6510	1.0460	2.534
FollTone(none)	-6.4530	2.5920	2.489
Tone(F)	16.8100	2.1400	7.854
Tone(H)	20.8600	1.8690	11.164
PrecTone(F)	1.5600	1.2560	1.242
PrecTone(H)	5.5420	1.3160	4.21
PrecTone(none)	7.9510	14.5000	0.548
PrecSegment(implosive) x cDur	-0.0352	0.0256	1.374
PrecSegment(none) x cDur	0.2035	0.1245	1.634
PrecSegment(voiced) x cDur	0.0359	0.0177	2.026
PrecSegment(voiceless) x cDur	-0.0492	0.0153	3.208
PrecSegment(vowel) x cDur	-0.1534	0.3299	0.465
FollSegment(implosive) x cTime	0.0083	0.0048	1.724
FollSegment(none) x cTime	-0.0098	0.0046	2.146
FollSegment(voiced) x cTime	-0.0042	0.0029	1.43
FollSegment(voiceless) x cTime	-0.0034	0.0027	1.259
FollSegment(vowel) x cTime	0.0450	0.0250	1.8
cDur x FollSegment(implosive)	0.0003	0.0349	0.01
cDur x FollSegment(none)	0.2212	0.0311	7.106
cDur x FollSegment(voiced)	-0.0162	0.0174	0.932
cDur x FollSegment(voiceless)	0.0033	0.0159	0.206
cDur x FollSegment(vowel)	-0.0996	0.1154	0.863
cDur x cTime	0.0001	0.0000	2.35
cTime x FollTone(F)	0.0000	0.0030	0.011
cTime x FollTone(H)	-0.0006	0.0028	0.233

Table 21 continued

	Estimate	Std. Error	t value
cTime x FollTone(none)	0.0081	0.0041	1.975[57]
FollTone(F) x Tone(F)	-2.8540	1.7790	1.604
FollTone(H) x Tone(F)	-2.5900	1.4800	1.75
FollTone(none) x Tone(F)	-4.0300	2.4530	1.643
FollTone(F) x Tone(H)	-3.1580	1.6390	1.928
FollTone(H) x Tone(H)	-5.0710	1.3880	3.655
FollTone(none) x Tone(H)	-2.4600	2.3080	1.066
Tone(F) x PrecTone(F)	-0.8986	1.8490	0.486
Tone(H) x PrecTone(F)	1.3000	1.6040	0.81
Tone(F) x PrecTone(H)	0.6301	1.6930	0.372
Tone(H) x PrecTone(H)	-2.1320	1.5220	1.401
Tone(F) x PrecTone(none)	-8.5400	2.1000	4.066
Tone(H) x PrecTone(none)	-10.2100	1.7910	5.704
cTime x Tone(F)	-0.0150	0.0034	4.391
cTime x Tone(H)	-0.0126	0.0028	4.416
cTime x PrecTone(F)	-0.0060	0.0034	1.784
cTime x PrecTone(H)	-0.0064	0.0027	2.403
cTime x PrecTone(none)	0.0182	0.0438	0.417
PrecSegment(implosive) x Tone(F)	-5.6230	2.4170	2.326
PrecSegment(none) x Tone(F)	-23.3300	15.2600	1.529
PrecSegment(voiced) x Tone(F)	-10.9000	1.8010	6.052
PrecSegment(voiceless) x Tone(F)	-0.3583	1.9220	0.186
PrecSegment(vowel) x Tone(F)	-10.3100	43.6700	0.236
PrecSegment(implosive) x Tone(H)	-1.0710	2.2610	0.474
PrecSegment(none) x Tone(H)	-15.5000	14.6600	1.057
PrecSegment(voiced) x Tone(H)	-4.9470	1.5410	3.211
PrecSegment(voiceless) x Tone(H)	-0.2648	1.6620	0.159
PrecSegment(vowel) x Tone(H)	-12.5100	32.7000	0.382

[57] This level is significant at $p < 0.05$.

The withheld values in this model are different than those in the other two; withheld segmental values are *sonorant* and withheld tone values are *low*. While this does not affect the significance of a factor, it does change the evaluation of individual levels of a factor, and the estimated values are relative to the withheld values.

In addition to the added Tone factors, the factor FollowingSegment is also added to this model; in the model, a following voiceless obstruent lowers F0.

While the previous model had only five interaction factors, the current model has ten, given in Table 22. It was not possible to cross most tone and segment factors due to partial predictability for initial and final vowels.

Crossed Effect	Significance
PrecedingSegment x cDuration	The effects of a preceding segment on Median F0 vary according to the duration of the vowel. Significant for voiceless, slightly mitigating the onset effect in longer vowels.
FollowingSegment x cDuration	The effects of a following segment on Median F0 vary according to the duration of the vowel. However, this is actually only an edge effect for final vowels; no consonant is significantly different from sonorant.
Tone x PrecedingTone	This is also an edge effect; F0 is significantly lower for a high tone at utterance onset.
Tone x FollowingTone	A high and low tone are modified differently when the following tone is high.
Tone x cTime	The effect of a tone varies with respect to time. High tones decline faster than low tones, again indicating pitch range compression.
PrecedingTone x cTime	
FollowingTone x cTime	This is in essence an edge effect; the declination rate is very small in final vowels.
cDuration x cTime	Duration and time interact with each other; this raises the Median F0 value for longer vowels that are later in the utterance.
FollowingSegment x cTime	Again, this is an edge effect, slightly increasing the declination rate in final syllables of longer utterances.
PrecedingSegment x Tone	The effects of a preceding segment vary depending on the tone. Significant levels are voiceless x high, implosive x falling, and voiced x falling.

Table 22. Crossed Effects in Median Model Using Tone Factors

It is clear from this table that many of the differences between the two models arise from the fact that the Preceding and Following Tone factors include edge effects, whereas Span and FollowingSpan did not. The PrecedingSegment x Tone factor is also of questionable value; it negates the individual significance of the levels *implosive*, *voiced*, and *voiceless* of PrecedingSegment, and many levels show large values with large standard errors; this is likely due to extremely small numbers of samples for some categories.

Consequently, this model functions quite differently from the model using Span factors. Further testing is needed to determine whether, setting edge effects aside, tone or span yields a better model of F0 in Bade. However, since the idea of a Span has received far less attention in the phonetic literature, the model presented in the following section includes only span values.

4.3 Modeling multiple time points for each syllable

While the previous section demonstrates that both span and syllable type have an effect on the median F0 of a vowel, this captures only a broad view of F0 movement. Segmental effects tend to be strongest at the beginning of the syllable (Hombert, Ohala, & Ewan, 1979), and in tone languages, the effect often vanishes partway through the vowel. I have also made claims about the specific alignment of a span within a syllable; if these claims are reflected in the phonetics, they too are best observed by measuring individual time points within the syllable.

Thus, while the data in this section come from the same set of utterances as the data for the Median model, the data themselves are different. Using a Praat script, F0 was measured at the onset of a vowel as well as at 5 ms, 10 ms, 20 ms, 30 ms, and 40 ms. F0 was further measured every 20 ms throughout the remainder of the vowel. In addition to these values, F0 measurements were also made every 20 ms during sonorants.

To create the final data set, extreme outliers were removed for each relative time value up to 60 ms, and also from the remaining points. In this way, 188 measurements were removed, or 1.1% of the total. The final data set contains 16918 measurements.

All of the factors listed in Table 15 are still applied in the current model. These factors also have the same levels, with the exception of Tone, which has the additional level *unspecified* for sonorants that lack lexically specified tone. Finally, Span and Following Span no longer refer sharing a domain with the previous or following vowel but with the preceding or following segment. If a vowel shares a span with the preceding consonant, it will also be in the same span as the preceding vowel; however, coda sonorants are always included in the span of the nucleus vowel (see 3.1, 3.3.7). While this model retains the previous centered Time factor, it also adds a RelativeTime factor, which measures distance from segment onset.

The RelativeTime values are not centered with respect to the mean since they are made at consistent intervals and this distance is always of interest. It is clear from examining the data that the F0 trajectories over a segment are not linear in nature. In particular, the segmental effects are non-linear with respect to time. As a first attempt to model this effect, I chose the inverse, $f(x) = x^{-1}$, since, conceptually, F0 moves from its perturbed value towards a specific target value, rapidly at first, and then leveling out. It will be seen that this effect is highly significant. Nevertheless, this model should be seen as the first step in fitting a model to the serial data; while the R^2 fit is comparable to the previous model, and the residuals show some non-normality.

FollowingSegment is the other new factor added; the new factors are listed in Table 23. SyllablePosition (onset, nucleus, coda) was originally considered as well, but this proved to be unnecessary, and in fact impossible, in the final model, since this value can be deduced from SyllableType, PrecedingSegment, and FollowingSegment.

Factor	Levels	Comments
Following Segment	Voiced, voiceless, implosive, sonorant, vowel, none	This is the immediately following segment.
RelTime	Continuous	Time relative to vowel onset. Measurements made as indicated above.
InverseRT	Continuous	1/(RelTime + 1); 1 is added to avoid division by 0. See text below.

Table 23. Additional Factors for Serial Model

Because of the large number of factors, a highly complex model is possible. Choosing a model is further complicated by the high correlation between certain factors (or even exact correlation, in the case of RelTime and InverseRT). For the sake of simplicity, I considered only two-way interactions except in the case of interactions that were of special interest: those representing an interaction between time, span structure, and tone. The interactions tested and found to be significant are given in Table 24; these include many that were tested for the Median model and found not to be significant.

Crossed Effect	Significance
SyllableType x cDuration	The vowel of a closed syllable is shorter in duration than the vowel of an open syllable. Together, this has a minor effect on F0.
Tone x FollowingSpan	The effects of being in the same span as the following segment are different for different tones.
Tone x Span	The effects of being in the same span as the preceding segment are different for different tones.
Tone x cTime	The joint effect of high tone and span on F0 is further modified by their position in time.
FollowingSpan x cTime	The effect of a segment being in the same span as the following segment varies with respect to time.
PrecedingSegment x cTime	The effect of a preceding segment varies with respect to time; based on the division of the numbers, this may be mostly an effect of position within the syllable.
cDuration x RelTime	The rate of F0 declension within a segment varies depending on the length of the segment; this could be an effect of fitting the tone to the segment.
Tone x cDuration	The F0 of the tone varies depending on the duration of the segment. This also could be an effect of fitting tone to segment.
Tone x RelTime	Tones change in different ways with respect to time. This is expected since falling tone is included in the model. The values for high, low, and unspecified tone are quite close to one another.
cDuration x InverseRT	The shape of F0 declension within a segment also varies depending on the length of the segment; again, this could be an effect of fitting tone to segment.
InverseRT x Edge	Tones have a different shape at the edge of an utterance.
Tone x Edge	Tones have a different overall F0 value at the edge of an utterance.
cTime x Edge	F0 declines differently at the edge of an utterance.
Tone x cTime	Tones have a different overall F0 value depending on where they occur in the utterance.
Span x cTime	The effect of a segment being in the same span as the preceding segment varies with respect to time.
RelTime x FollowingSpan	The effect of the following span is different at different points in the syllable.
RelTime x Span	The effect of the preceding span is different at different points in the syllable.
Span x FollowingSegment	The effect of a preceding span differs depending on the following segment; this seems to be primarily an effect of position within the syllable and is strongest for segments in utterance-final or syllable-initial positions.
FollowingSpan x FollowingSegment	The effect of a following span differs depending on the following segment. There is no apparent direct correlation to position within the syllable.

InverseRT x FollowingSegment	The effect of a following segment differs inversely with respect to the distance from that segment. This effect does not seem to apply in syllable onset.
cTime x FollowingSegment	The effect of a following segment differs with respect to its distance from the beginning of the utterance.
PrecedingSegment x RelTime	The effect of a preceding segment differs over the course of the segment.
PrecedingSegment x InverseRT	The effect of a preceding segment varies inversely with respect to distance from segment onset.
Tone x cDuration x RelativeTime	The declension of a tone within a segment varies depending on the duration of that segment.
Tone x cTime x Span	The interaction between span and tone varies with respect to position in the utterance.
Tone x RelTime x FollowingSpan	The interaction between tone and following span varies with respect to the distance from segment onset.
Tone x cTime x Following Span	The interaction between tone and following span varies with respect to the distance from utterance onset.
Tone x RelTime x Span	The interaction between tone and preceding span varies with respect to the distance from the segment onset.

Table 24. Crossed Factors in Serial Model

The final model also includes Speaker and Utterance as random effects, with random intercepts for speaker and random slopes by cTime and intercepts for Utterance. The interaction between cTime and intercept for Utterance is significant in this model. The final model has an R^2 value of 0.757, with 67.6% of the variance predicted by the random effects.

Because there is so much interaction among factors, it is not especially helpful to examine individual effects. The estimated coefficients and the supporting MCMC sample are given in Table 29 and Table 30, respectively, in the appendix. Many results can be examined from this model; however, I focus on the effects of preceding segments, span, and following span.

4.3.1 Effects of preceding segments

The graph in Figure 9 shows the modeled effects of the preceding segment on F0 in Bade. In particular, this is the predicted effect of the preceding segment on the F0 of a high tone segment with average duration (77 ms) with onset at cTime = 100 ms. Preceding and following spans are assumed to be different, the syllable type is open, and the following segment is a sonorant.

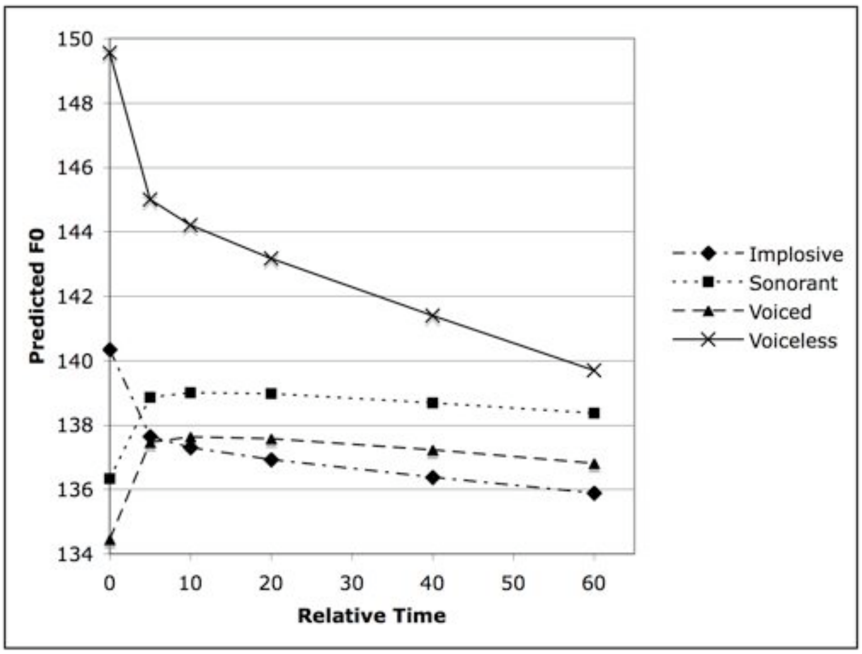


Figure 9. Predicted Effect of Preceding Segment on F0

Figure 9 shows that voiceless segment cause F0 to fall rapidly at first and then more slowly, but even at 60 ms, the F0 is still higher for segments following a voiceless consonant. Segments following a voiced obstruent or sonorant both rise significantly at the onset and then show a small rate of declension throughout the remainder of the segment. Sonorant values are slightly higher than voiced values throughout. Finally, the F0 curve for segments following an implosive has a similar shape to that of the F0 curve following voiceless obstruents, but it is considerably lower, and by 10 ms, it has the lowest value of any of the four curves.

This corresponds well to the effects shown in the median model in section 4.2.3, especially since that model is designed to avoid onset effects and omits the first 10 ms of longer vowels. From the serial model, we see two independent patterns emerge. At segment onset, the preceding segment effect yields the following hierarchy:

125. Voiceless > Implosive > Sonorant > Voiced

However, by 20 ms into the segment, the hierarchy in (126) holds instead:

126. Voiceless > Sonorant > Voiced > Implosive

As a rough test of the significance of these hierarchies, the model was rerun with each of these four levels withheld. For the factor PrecedingSegment itself, all pairs are significantly different except *sonorant* and *voiced*. For PrecedingSegment x RelTime, *voiceless* is significantly different from the other three factors. For PrecedingSegment x InverseRelTime, *voiceless* and *implosive* are significantly different from *sonorant* and *voiced*. However, cTime x PrecedingSegment shows significant differences for all pairs.

When examining the effects of consonants on tone, this makes it clear that it is necessary to establish a baseline for comparison. If this baseline compares the slope of the pitch curve over the first 10 ms to 0, then implosives and voiceless obstruents, with a negative slope, raise F0 and sonorants and voiced obstruents, with a positive slope, lower F0 in Bade. However, since these effects persist well into the vowel, this is not the only reasonable comparison to make. If sonorant is taken as the baseline, and the measurements are made beginning at 10 ms, then sonorants by definition are neutral, voiceless obstruents are pitch raisers, and voiced obstruents—both implosives and non-implosive voiced obstruents—are pitch lowerers. This persistence of consonantal effects past 60 ms is surprising, given the proposal that consonant effects are minimized in tone languages; they persist in Yoruba for 40-60 ms and in Thai for 30-50 ms (Hombert, Ohala, & Ewan, 1979).

These varying effects may help to explain apparent contradictions in the literature regarding implosives. While very few thorough studies of implosives on F0 exist, they have been claimed both to be both pitch raisers and pitch lowerers (see Frazier, 2008; Odden, 2004). This may be partially an artifact of methodology—first, in that the effect may vary depending on where in the vowel a measurement is made in other languages, as it does in Bade, and second, in that it is not always clear how to select a baseline for comparison.

Nevertheless, in Bade, since implosives have both a raising and a lowering effect on F0, the phonetics do not *a priori* predict a specific interaction with tone. Similarities can be found with each of the other consonant types, as can differences. Perhaps it is not surprising, then, to find that they are phonologically neutral.

Also, if there is a direct connection between the phonetics of microprosody and the phonological interaction between consonants and tone, then the sonorant data also indicate that the evaluation of the microprosodic effect must be somewhat abstract. Sonorants are neutral in that they fall between the high values of the voiceless onset and the low values of the voiced onset, but they show a clear similarity in shape to the voiced obstruents and a clear dissimilarity to the voiceless ones; they are also much closer in value to the voiced obstruents. Nonetheless, sonorants are neutral in Bade.

4.3.2 Effects of spans

The effect of spans on F0 across the first 60 ms of a vowel is illustrated in Figure 10. The effects are illustrated for both high and low tones. Segments are of average duration in open syllables with sonorants as both the preceding and following segment; this choice ensures that only vowels are taken into consideration. The cTime values are set at 100 ms at vowel onset.

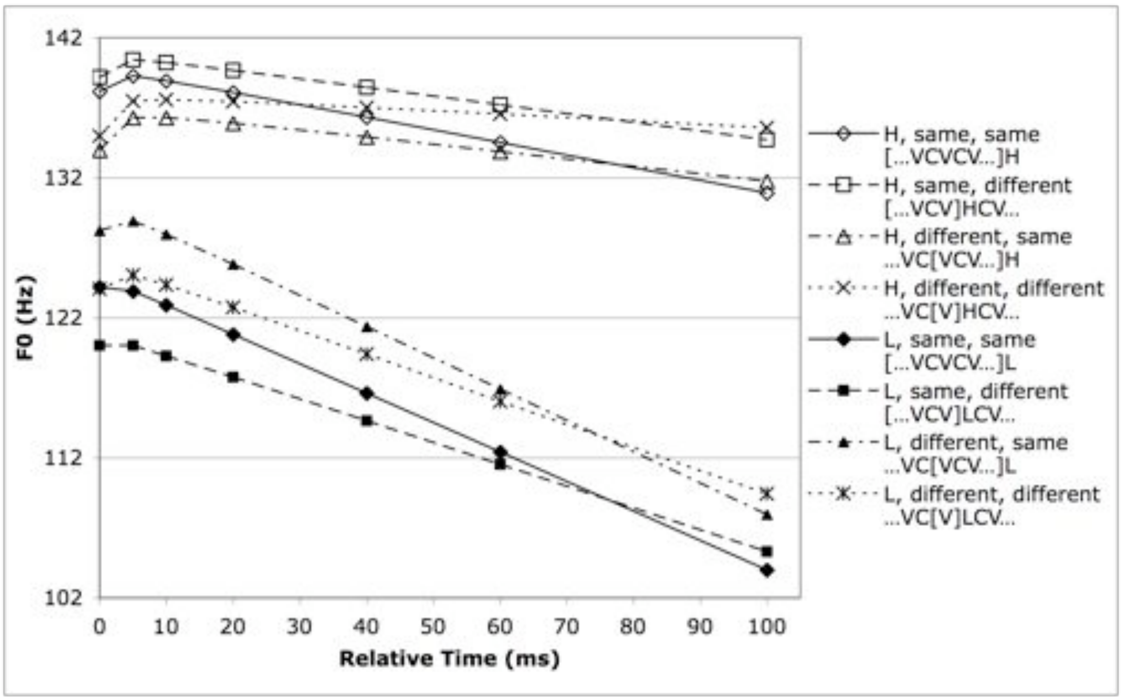


Figure 10. Modeled Effect of Span and FollowingSpan on F0 for High and Low Tones

The high tone vowels behave as expected with respect to Span. The vowels that are in the same span as the previous segment are higher throughout the first part of the vowel than those that are in a different span. Moreover, the vowels in the same span as the previous segment appear to reach their highest point slightly sooner than those that are in a different span; the high tone vowels in the same span clearly start to decline between 5 and 10 ms, while those in a different span from the previous segment increase their rate of declination after 10 ms. Thus, those vowels in the same span as the preceding segment also show a smaller consonant effect from the preceding segment.

However, the behavior of high tone vowels with respect to the following span is unexpected. Here, the vowels that are in a different span have a higher overall F0 than the corresponding same span vowels, and they also decline at a slower rate. This is puzzling; as previously mentioned, it may be the result of a dissimilatory effect between spans.

The low tone vowels show the same effect as the high tone vowels with respect to the consonant effect; those vowels in the same span as the previous vowel show a much smaller effect from a preceding consonant than those vowels in a different span do. This may indicate that F0 is maintained throughout the preceding segment when it is in the same span as the vowel. They also show the same declination effects based on the following span: if a vowel is in the same span as the following segment, this results in a much more rapid declination rate. Overall, low tones also decline at a faster rate than high tones do. However, in terms of absolute F0 levels, the low tones essentially mirror the high tone patterns: if the vowel is in a different span from the preceding segment, then its F0 is higher at vowel onset and as far as 100 ms into the vowel. Again, this is somewhat puzzling; it is possible that this is, in part, an effect of model construction, since it would often be the case that a *different* value would indicate a either a preceding high tone or a preceding voiceless obstruent, both of which raise F0. It is also possible, as previously mentioned, that high and low tones are maximally distinguished from one another within a span.

These results correspond quite well to the median results in section 4.2.2. However, since this model also measured F0 values for sonorants, these can also be compared for span effect.

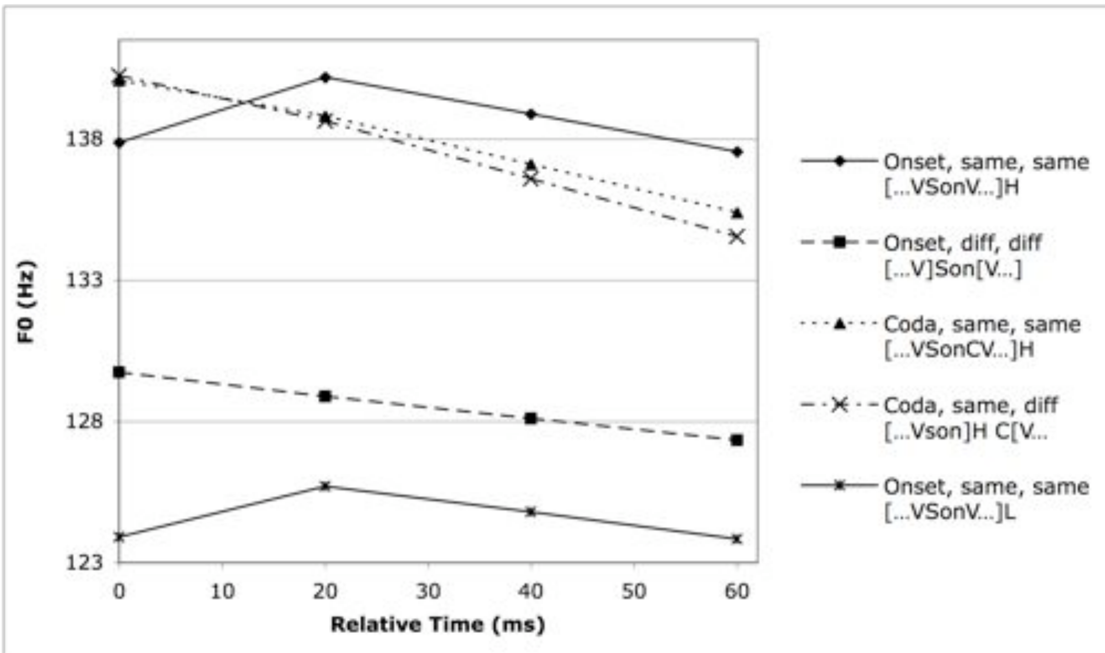


Figure 11. Predicted Effect of Preceding and Following Span on Sonorants in Onset and Coda Position

Figure 11 illustrates the predicted behavior of tone in sonorants with respect to position, span, and following span. For the onset segments, FollowingSegment must be a vowel, and PrecedingSegment is also set at *vowel*. Since a sonorant in onset position is assumed not to have a lexical tone assigned to it, the values for Span and FollowingSpan must match; the values ‘different, different’ in this case indicate that the segment is not in a span at all, and consequently, that the tone is unspecified. For sonorants in onset position that are in a span, high and low tones are compared. For the coda sonorants, the assumptions are different; PrecedingSegment must be a vowel, and FollowingSegment is arbitrarily set at *voiceless*. Coda sonorants are assumed to be part of the same span as the vowel in the syllable in which they occur—a choice supported by the fact that there is little F0 transition effect between segments—so these segments are compared only for FollowingSpan; I show only high tone values. For each segment modeled in Figure 11, SyllableType is closed, cDur is 0, and cTime begins at 100 ms.

The model indicates that there is a large difference between sonorants that are located in a span and those that are not located in a span; the sonorant that is not in a span has a neutral F0 value, closer to the low tone segment than the high tone one. The segment contained in a span declines at a faster rate than the one that is not contained in a span. The coda segments also show span effects. These effects are negligible at onset, but the sonorant that is not in the same following span declines at a more rapid rate, as is expected; there does not seem to be a dissimilatory effect between sonorants and vowels. The apparent small effect size of preceding segment in coda position actually results from the factor FollowingSegment x InverseRelativeTime; this would likely be better expressed with an added factor representing syllable position.

4.4 Limitations

While the mixed effect method is a far more reliable and straightforward approach to an unbalanced set of data than other potential approaches, like any other, the model is limited by its input. Some types of data are underrepresented in this data set, and mixed effect models are quite sensitive to outliers—consequently, if the underrepresented points are not in fact representative, this will have a negative impact on the accuracy of the model.

One area of underrepresentation in this model is the number of speakers. With only three speakers, the MCMC calculations for random effects in both models show a large range in the 95th percentile confidence intervals, with a mean parameter of 13.64 but a confidence interval of 4.8 to 49.7 for the median model. This range would presumably become smaller with a larger number of male speakers.

Also, as previously mentioned, the serial model cannot be completely fitted by a linear model. While adding an inverse time factor greatly improved the fit, this can and should be further modified to better understand the interactions between segments, spans, and tones. Moreover, it may be profitable to include preceding and following tone values in the serial model.

For any of the models, a restructuring of the data with fewer dependencies between factors may yield a model that shows interactions in a more intuitive manner; for example, if the right and left edge of the model were not marked by levels of preceding and following segment and tone, the median model with tone factors might be more straightforward.

Finally, there are types of measurements excluded from the model that might be useful to include in a future version. Vowel length is contrastive in Bade, and it is conceivable that this would be a better predictor than vowel duration. More importantly, vowel quality is known to affect F0, and this was not marked in the data. Utterance length is also a potentially important factor that is not included in these models.

4.5 Summary

The mixed effects models prove very useful in examining the Bade data, since they are able to isolate individual effects even within a large and varied corpus. Both span models show that the effects of a preceding segment on F0 are significant, as are the effects of the segment's inclusion in or exclusion from the preceding and following span. However, while these effects correspond partially to the phonological model established in the previous chapter, these results also show that there is not an absolute correspondence between the phonological model and the phonetic implementation.

In addition, these results are valuable in that they provide the only existing phonetic study of Bade data, and they are among few studies of the microprosodic effects of implosives. They also add to a more sizeable literature that examines the phonetics underlying consonant-tone interaction, and to a very small linguistic literature using mixed effect models.

Chapter 5 Conclusion

This research set out to discover how and why consonants and tones interact with each other. In Chapter 2, I addressed this question from the perspective of a cross-linguistic survey of consonant-tone interaction. The results show that, while the more commonly studied interaction between voicing and low tone is the most frequent type of consonant-tone interaction, consonant-tone interaction also includes a much larger variety of consonants than has previously been assumed. It also includes a wider variety of tone types than have been assumed by earlier phonological models.

The survey, along with the phonetic connection between the realization of laryngeal features and the production of F0, becomes the basis for the theoretical approach in Chapter 3. I discuss the concept of a tone span and argue that this provides a basis for an interaction between a suprasegmental feature and a segmental feature without merging the two features into one; because many consonants are able to interact with tone, I argue that a merged feature approach cannot account for the full range of data.

I further explore these ideas by providing a detailed account of the phonology of two typologically distinct languages, Bade and Kam. The careful study of these two languages provides further insight into the diversity of behavior that exists for a single category of phonological behavior. However, all constraints on the interaction of consonants and tones can be expressed in terms of logical combinations of a tone feature and one or more consonant features; these constraints either require that a certain laryngeal feature occur within a certain tone span or prohibit a feature from occurring within a span.

Finally, in Chapter 4, I examine the F0 patterns in Bade to see how the phonology is reflected in the phonetics. The results are expected in the sense that voiced obstruents, with a low tone affinity, lower F0 and voiceless obstruents, with a high tone affinity, raise F0, while sonorants have an intermediate effect on F0 and are neutral with regard to consonants. However, while implosives are also neutral with regard to consonant-tone interaction, the phonetics do not predict this. Vowels following implosives have the lowest mean F0 value, and after 10 ms, the lowest F0 value of any consonant type. On the other hand, at vowel onset, the vowel following an implosive falls significantly, like that of a voiceless obstruent, while the vowel following a voiced obstruent rises significantly. If there is a phonetic motivation for the neutrality of implosives in Bade, perhaps it results from the mixed cues. The results in Chapter 4 also show that the tone span, marked with the phonological boundaries hypothesized for Bade, is also a phonetically distinct unit for F0 measurement. However, the results only partially match the prediction that F0 will remain relatively constant throughout the span.

5.1 Directions for Future Research

Because both the topic of consonant-tone interaction and the majority of the languages in which it occurs have received relatively little attention in the literature, the research contained in this dissertation should be viewed as a starting point rather than a final statement on the issue. There are numerous areas where more research is needed.

5.1.1 Descriptive work

Though some languages included in the survey, such as Korean and Thai, have numerous descriptions published, others, such as Kam, have only basic descriptions available. The basic patterns described for Kam have been verified in published phonetic work, but often, the patterns described here are known only from impressionistic comments. In a language like Kam, where the consonant-tone interaction is phonotactic in nature, the description of the environment is straightforward. However, in a language like Bade, consonant-tone interaction is intimately tied to all aspects of tone in the language, and the tone patterns addressed in Chapter 3 only begin to demonstrate the complexity that is found in the tone system; the effect of consonants on verbal paradigms is not included in the analysis there. Even in this language, which is relatively well-described compared to many languages in the survey, there are also still open questions regarding many basic aspects of the tone system, including the distribution of falling tones, the existence of downstep, the syntactic boundaries that block tone spreading, and the effect of intonation on the realization of lexical tone.

It is also the case that the data reported for some languages in the survey may be inaccurate. For example, Kera is often used as an example of a language with long distance voicing assimilation; there is debate about whether this assimilation is direct or mediated through tone (Hansson, 2004a; S. Rose & Walker, 2004). While no participant in this debate has deliberately misrepresented the data, Pearce (2007) shows that Kera consonants are not, in fact, voiced. It may be, then, that careful phonetic examination of the sounds in the languages included here would eliminate some of the categories in the survey that currently show split behavior—for example, consonants may be miscategorized, or the contrast attributed to the consonant may be more appropriately assigned to the vowel. While it seems unlikely that all of the languages in a specific category are incorrectly described, it is possible that a phonology that is more directly based on the phonetics could be found.

5.1.2 Psychological Reality

I have hypothesized that the phonotactic pattern described in Kam is psychologically real and requires phonological explanation. Others would argue that it is merely historical and therefore does not belong to the phonology at all. However, no experimental work has been conducted in Kam to attempt to verify either claim, nor is there any experimental work that tests the psychological reality of this type of pattern in any other language. In order to move this debate from the theoretical level to the practical one, such experiments are sorely needed.

5.1.3 Phonetic Implementation

While the experimental design implemented in Chapter 4 may not be optimal, it is extremely practical, in that it offers a way for statistically significant phonetic knowledge to be gleaned from a small corpus of field data. This is of immense value in working with endangered languages in general. Specific to the issues addressed here, little is known about the phonetic implementation of a tone span. In order to verify that such a unit has measurable effects on F0, data from many more languages is needed. In determining whether a tone span includes the onset of a syllable, it may also be useful to collect data specifically addressing the timing of tone peaks and movement towards tone targets (Y. Xu & Wang, 2001).

5.1.4 Frequency

Interactions between voicing and tone are much more frequent than interactions between glottalization and tone. However, the reasons behind this are unclear. It may be that tone languages more often have a voicing contrast than a glottalization contrast—that consonant-tone interaction is equally likely for all consonant types but that not all consonant types are equally likely to occur. However, it is also possible that the phonetic correlation between voicing and lowered F0 is more consistent than other types of phonetic correlations, and consequently, the connection between voicing and low is more frequent in the phonology as well. Finally, it may be the case that a contrast is more likely to be incorrectly documented as being a voice contrast than it is to be incorrectly documented as a different type of laryngeal contrast and that the bias towards voicing in consonant-tone interaction is only apparent.

5.1.5 Beyond Tone

There are several areas where the type of approach taken here may prove useful. One is for other phonological interactions between unlike segments, such as consonants and vowels. While these interactions are often analyzed in terms of a merged feature or a geometric relationship, it is possible that the concept of a span would prove fruitful in explaining these interactions.

A second area where the research of consonant-tone interaction may prove useful is in understanding the role of post-lexical phonology in the larger grammar. In particular, the survey includes two languages in which intonation and consonants interact. It is possible that interactions of this sort could provide insight into the phonology-syntax interface.

Appendix A: Languages Included in Survey

This appendix lists languages included in Table 2 of Chapter 2. Languages are categorized according to language family, as listed in the Ethnologue (Gordon, 2005), in enough detail to provide general information about how closely these languages are related. Each language name is followed by common alternate names in parentheses where relevant, the primary country or countries where the language is spoken, and the source of the information on which its inclusion is based. Not all sources are primary.

Afro-Asiatic
- **Chadic**
  - **Biu-Mandara**
    - Mulwi (Musgu), Cameroon, Chad (Bradshaw, 1999)
    - Lamang (Moreton, 2006)
    - Kotoko (Zina dialect), Nigeria, Chad (Odden, 2004)
  - **Masa**
    - Masa (Masana), Chad, Cameroon (De Dominicis, 2001)
    - Musey, Chad (Shryock, n.d.)
  - **West**
    - Bade, Nigeria (Schuh, 2002)
    - Bole (Bolanci), Nigeria (Schuh, 2004)
    - Miya, Nigeria (Schuh, 1998)
    - Ngizim, Nigeria (Peng, 1992; Schuh, 1971, 2002)
    - Sayanci (Saya), Nigeria (Schneeberg, 1974)

Algic
- **Algonquian**
  - **Central**
    - Kickapoo, United States, Mexico (Gathercole, 1983)

Austro-Asiatic
- **Mon-Khmer**
  - **Northern Mon-Khmer**
    - Kammu (Khmu), Laos (Svantesson & House, 2006)

Austronesian
- **Oceanic**
  - **North New Guinea**
    - Yabem, Papua New Guinea (Hansson, 2004b)

Hmong-Mien
  Mienic
    Highland Yao (Iu Mien), China (Moreton, 2006)
Indo-European
  Germanic
    West
      Limburgian (Maasbracht dialect), Netherlands (Hermans & van Oostendorp, 2000)
  Indo-Aryan
    Northern zone
      Kangri, India (Eaton, 2007)
Iroquoian
  Southern Iroquoian
    Cherokee, United States (Wright, 1996)
Kiowa-Tanoan
  Kiowa-Towa
    Kiowa, United States (Watkins & McKenzie, 1984)
Na-Dene
  Athabaskan
    Canadian
      Carrier, Canada (Pike, 1986)
      Sekani, Canada (Hargus, 1985)
Niger-Congo
  Benue-Congo
    Bantoid
      Southern
        Makaa-Njem
          Makaa, Cameroon (Bradshaw 1999)
        Mijikenda (Cassimjee & Kisseberth, 1992)[58]
          Chichonyi (Chonyi), Kenya
          Chidigo (Digo), Kenya, Tanzania
          Chiduruma (Duruma), Kenya
          Chidzihana (Dzihana), Kenya
          Chikambe (Kambe), Kenya
          Chikauma (Kauma), Kenya
          Chirabai (Rabai), Kenya
          Chirihe (Rihe), Kenya
          Kigiryama (Giryama), Kenya
        Nguni
          Swati, South Africa, Swaziland (Downing & Schadeberg, 2007)
          Xhosa, South Africa (Bradshaw, 1999; Jessen & Roux, 2002; Lanham, 1958)

[58] Ethnologue groups many of these languages as dialects of Giryama.

Yaka, Democratic Republic of Congo, Angola (Bradshaw 1999)
Zulu, South Africa, (Downing & Schadeberg, 2007; Strazny, 2003)

Shona

Kalanga'a, Botswana dialect (Downing & Gick, 2001)
Nambya, Zimbabwe (Downing & Gick, 2001)

Gur

Dagara-wule, Burkina Faso (Bradshaw 1999)

Kru

Bassa, Liberia (Hobley, 1964)
Kuwaa, Liberia (Maddieson, 1978)

Kwa

Ebrié (Cama), Ivory Coast (Botma & Smith, 2006)
Ewe, Ghana, Togo (Bradshaw, 1999; Long & Zheng, 1988; Peng, 1992)
Tuwuli, Ghana (Harley, 2000)

Nupoid

Nupe, Nigeria (Bradshaw, 1999; Hyman, 1970; Peng, 1992)

Kordofanian

Heiban

Moro (Thetogovela dialect), Sudan (Jenks & Rose, Submitted)

North

Adamawa-Ubangi

Gbaya ɓokota, Central African Republic (Bradshaw, 1999)
Suma, Central African Republic (Bradshaw, 1999)

Otomanguean

Amuzgoan

Amuzgo, Mexico (Williams, 2005)

Mixtecan

Ayutla Mixtec, Mexico (Pankratz & Pike, 1967)
San Miguel el Grande Mixtec, Mexico (Tranel, 1995)

Sino-Tibetan

Chinese

Wu, China

Longyou dialect (Cao, 2002, cited in Zhang 2006)
Shaoxing dialect (Jixeng Zhang, 2006)
Songjiang dialect (Bao, 1999)
Wenling dialect (Bao, 1999)
Wenzhou dialect (P. Rose, 2002)
Wujiang dialect (Shen, 1994)
Wuyi dialect (Bao, 1999)

Tibeto-Burman

Himalayish

Thakali (Hari, 1971)

Jingpho-Konyak-Bodo

Jingpho, Myanmar (Maran, 1971)
Kachari, India (Hombert, Ohala, & Ewan, 1979)

Kuki-Chin-Naga

Zahao (Falam Chin), Myanmar (Yip, 1982)

Lolo-Burmese

Burmese, Myanmar (Lee, 2007; Maran, 1971)

Nungish

Rawan, Myanmar, India (Maran, 1971)

Tamangic

Manange, Nepal (Hildebrandt, 2003)

Tai-Kadai

Kam-Tai

Kam-Sui

Kam (Southern Kam, Dong), China (Long & Zheng, 1988)
Mulao (Mulam), China (Moreton, 2006)

Tai

Thai (Bangkok dialect), Thailand (Morén & Zsiga, 2006)

Tucanoan

Eastern Tucanoan

Wanano (Guanano), Brazil, Colombia (Stenzel, 2007)

Yanomam

Sanuma (Venezuela) (Borgman, 1990)

Isolate

Korean (Seoul dialect, Kyungsang dialect), Korea (Jun, 1993; Kenstowicz & Park, 2006; Silva, 2006)

Appendix B: Tables for Chapter 4

The *p*-values based on the *t*-distribution generated by the *lmer* function in *R* tend to be underestimated for small sample sizes. Thus, it is necessary to check the singificance of these values in some other way. Baayen (In press) recommend examining the posterior distribution through Markov Chain Monte Carlo (MCMC) sampling, obtained through *p-vals.fnc* in the *languageR* package (Baayen, 2007).

This appendix illustrates the difference between the two with a model originally considered for the Median values modeled in Section 4.2.2. This model is identical to the final model, given in (122), except that it adds a three-way interaction between cTime, Tone, and FollowingSpan; the two-way interactions between these factors are now automatically included in the model.

127. Median_F0 = PrecedingSegment + Edge
+ Duration x SyllableType + Span x Tone
+ **cTime x Tone x FollowingSpan**
+ [Utterance] + [Speaker] + [cTime | Utterance]
+ Intercept

The coefficients for this model are provided in Table 25. In particular, the |t| value for the factor cTime x Tone (H) x FollowingSpan (same) is 2.782, implying that this factor is significant since |t| > 2 typically corresponds to $p < 0.05$.

	Estimate	Standard Error	|t|
(Intercept)	133.2	6.275	21.223
Tone(H)	6.901	0.8377	8.237
Tone(L)	-6.24	0.8692	7.178
PrecSegment(none)	-2.076	4.356	0.476
PrecSegment(son)	3.587	0.9191	3.902
PrecSegment(vce)	0.8129	0.9475	0.858
PrecSegment(-vce)	7.203	0.9271	7.769
PrecSegment(V)	8.253	4.773	1.729
cDuration	0.008145	0.01681	0.485
SylType(open)	-3.117	0.5508	5.658
Edge(yes)	-5.005	0.5215	9.598
cTime	-0.02441	0.002375	10.279
FolSpan(same)	2.903	1.011	2.873
Span(same)	6.032	0.957	6.303
cDuration x SylType(open)	-0.05588	0.01768	3.16
Tone(H) x cTime	0.0006706	0.002697	0.249
Tone(L) x cTime	0.007635	0.002939	2.598
cTime x FolSpan(same)	-0.001997	0.004204	0.475
Tone(H) x FolSpan(same)	-3.469	1.23	2.82
Tone(L) x FolSpan(same)	-3.922	1.426	2.75
Tone(H) x Span(same)	-3.624	1.132	3.201
Tone(L) x Span(same)	-10.53	1.427	7.382
Tone(H) x cTime x FolSpan(same)	0.01486	0.00534	2.782
Tone(L) x cTime x FolSpan(same)	0.002567	0.005387	0.477

Table 25. Model Coefficients for Median F0 with Additional Three-way Interaction

However, the *p*-values obtained from a MCMC sample, with sample size 10000, imply that the *t*- values in Table 25 are too large. Table 26 lists the model estimate for each coefficient, followed by the mean value for that coefficient in the MCMC sample. The next two columns provide the lower and upper Bayesian highest posterior density confidence intervals (HPD), with confidence levels of 95%. Finally, the last two columns compare the *p*-values for the posterior distribution and the *t*-distribution, respectively. The bolded values show a difference in significance between the two estimates. In particular, the three-way interaction does not reach significance. On the other hand, the interaction between Tone(H) and Span(same) is now found to be significant for the MCMC *p*-value. Thus, the three-way interaction is excluded from the final model.

The MCMC results for the final model are provided in Table 27. For the final model, two levels of factors are seen to have misleading *t*-statistics, but overall, the same factors are significant according to both methods of calculation.

	Estimate	**MCMC Mean**	**HPD95 Lower**	**HPD95 Upper**	***p*-val MCMC**	**Pr(>|t|)**
(Intercept)	133.1689	134.8157	110.4326	158.9199	0.0022	< 0.0001
Tone(H)	6.9005	6.4142	4.5792	8.3227	0.0001	< 0.0001
Tone(L)	-6.2396	-6.0384	-8.0228	-4.0822	0.0001	< 0.0001
PreSeg(none)	-2.0758	-3.8156	-13.4648	5.8134	0.4406	0.6338
PreSeg(son)	3.5865	2.0945	0.0332	3.9696	0.0368	0.0001
PreSeg(vce)	0.8129	-1.0771	-3.0713	1.0561	0.3144	0.391
PreSeg(-vce)	7.2027	4.7534	2.8611	6.806	0.0001	< 0.0001
PreSeg(V)	8.2525	6.344	-4.5232	16.3705	0.238	0.084
cDur	0.0081	0.0016	-0.0335	0.0385	0.9328	0.6281
SylTyp(open)	-3.1167	-3.0594	-4.2145	-1.8088	0.0001	< 0.0001
Edge(yes)	-5.0047	-4.8645	-6.0191	-3.7559	0.0001	< 0.0001
cTime	-0.0244	-0.0271	-0.0324	-0.0223	0.0012	< 0.0001
FolSp(same)	2.9028	4.5018	2.2218	6.6552	0.0002	0.0041
Span(same)	6.0317	5.5212	3.4209	7.6618	0.0001	< 0.0001
cDur x SylTyp(open)	-0.0559	-0.0577	-0.0975	-0.0201	0.0024	0.0016
Tone(H) x cTime	0.0007	0.0063	0.0003	0.0122	**0.0404**	**0.8036**
Tone(L) x cTime	0.0076	0.012	0.0055	0.0185	0.0004	0.0095
cTime x FolSp(same)	-0.002	0.0023	-0.0071	0.0114	0.616	0.6348
Tone(H) x FolSp(same)	-3.4694	-4.8154	-7.4729	-2.0243	0.0004	0.0049
Tone(L) x FolSp(same)	-3.9219	-5.8467	-9.0864	-2.7226	0.0002	0.006
Tone(H) x Span(same)	-3.6243	-2.479	-5.1224	-0.0551	**0.0546**	**0.0014**
Tone(L) xSpan(same)	-10.5331	-10.0853	-13.1771	-6.9804	0.0001	< 0.0001
Tone(H) x cTime x FolSp(same)	0.0149	0.0098	-0.0022	0.0216	**0.1078**	**0.0055**
Tone(L) x cTime x FolSp(same)	0.0026	-0.0039	-0.016	0.008	0.5192	0.6338

Table 26. MCMC Results for Median Model

The remainder of this appendix contains tables for the other models in Chapter 4.

	Estimate	**MCMC Mean**	**HPD Lower**	**HPD Upper**	***p*-val MCMC**	**Pr(>|t|)**
(Intercept)	133.3686	135.0381	109.632	161.0141	0.0026	< .0001
Tone(H)	6.4833	6.1143	4.3462	7.9853	0.0001	< .0001
Tone(L)	-6.4087	-6.3016	-8.2324	-4.3393	0.0001	< .0001
PreSeg(none)	-1.7168	-3.5091	-12.6876	6.3606	0.472	0.6941
PreSeg(son)	3.4884	1.9407	-0.0455	3.9564	**0.0564**	**0.0002**
PreSeg(vce)	0.7453	-1.1573	-3.1243	0.9632	0.2732	0.4322
PreSeg(-vce)	7.2334	4.7739	2.7642	6.7287	0.0001	< .0001
PreSeg(V)	8.3196	6.3919	-3.7747	17.0243	0.228	0.0821
cDur	0.0056	-0.0001	-0.0366	0.0347	0.9986	0.7395
SylTyp(open)	-3.0332	-2.9772	-4.2316	-1.7706	0.0001	< .0001
Edge(yes)	-5.2781	-5.145	-6.2814	-4.0193	0.0001	< .0001
cTime	-0.026	-0.0276	-0.0322	-0.0232	0.001	< .0001
FolSp(same)	3.0645	4.4704	2.3298	6.7208	0.0001	0.0023
Span(same)	5.915	5.4242	3.2022	7.4514	0.0001	< .0001
cDur x SylTyp(open)	-0.0538	-0.0568	-0.0942	-0.0171	0.0034	0.0024
Tone(H) x cTime	0.0044	0.0086	0.0033	0.0134	0.001	0.0569
Tone(L) x cTime	0.0082	0.0105	0.0049	0.0159	0.0001	0.001
Tone (H) x FolSp(same)	-4.111	-5.3151	-8.0648	-2.5642	0.0002	0.0007
Tone(L) x FolSp(same)	-3.9535	-5.3862	-8.4008	-2.2727	0.001	0.005
cTime x FolSp(same)	0.0045	0.0045	0	0.0088	0.0498	0.0233
Tone(H) x Span(same)	-3.2367	-2.1709	-4.6417	0.3658	**0.0912**	**0.0041**
Tone(L) x Span(same)	-10.6156	-9.9393	-13.1291	-6.9621	0.0001	< .0001

Table 27. MCMC Values for Final Median Model

Table 28. MCMC Values for Median Model with Preceding and Following Tone

	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	Pr(>|t|)
(Intercept)	123.0205	124.7204	99.7854	152.3276	0.0032	0
PrecSeg(imp)	-0.9087	0.339	-3.6265	4.2294	0.8614	0.6217
PrecSeg(none)	5.5866	10.6897	-14.6142	36.867	0.4186	0.629
PrecSeg(vce)	-0.755	-1.0794	-3.3627	1.1616	0.3468	0.4636
PrecSeg(-vce)	2.9056	1.36	-1.7397	4.798	0.4238	0.0567
PrecSeg(V)	10.9602	6.8855	-14.6093	30.2496	0.5438	0.2821
cDur	-0.0234	-0.0355	-0.0656	-0.0041	0.0222	0.0969
FollSeg(imp)	0.6324	2.8364	-0.0287	5.7804	0.0552	0.6238
FollSeg(none)	2.0319	4.329	0.7753	8.173	0.02	0.2369
FollSeg(vce)	-0.76	0.237	-1.407	2.0227	0.7784	0.3329
FollSeg(-vce)	-2.3496	-2.5868	-3.9096	-1.213	0.0004	0.0002
FollSeg(V)	-1.0684	-0.7643	-5.7309	4.1956	0.7544	0.6381
cTime	-0.0089	-0.0115	-0.021	-0.002	0.0192	0.0422
SyllType(open)	-1.8351	-2.3997	-3.7946	-0.9744	0.0008	0.0049
FollTone(F)	4.3674	4.7126	1.9245	7.5283	0.0016	0.0006
FollTone(H)	2.651	2.5146	0.1673	4.801	0.0332	0.0113
FollTone(none)	-6.4526	-8.5913	-14.2557	-2.4526	0.0048	0.0129
Tone(F)	16.8052	17.2608	12.5371	21.8417	0.0001	0
Tone(H)	20.8633	19.5405	15.5286	23.4444	0.0001	0
PrecTone(F)	1.5596	0.735	-2.1527	3.4277	0.6034	0.2144
PrecTone(H)	5.542	4.6042	1.7782	7.5261	0.0008	0
PrecTone(none)	7.9513	24.8544	-6.2359	57.3533	0.1288	0.5836
PrecSeg(imp) x cDur	-0.0352	-0.0204	-0.0806	0.0347	0.4986	0.1695
PrecSeg(none) x cDur	0.2035	0.1586	-0.1348	0.4293	0.2774	0.1025
PrecSeg(vce) x cDur	0.0359	0.0314	-0.0073	0.0705	0.114	0.0429
PrecSeg(-vce) x cDur	-0.0492	-0.0638	-0.0983	-0.0289	0.0002	0.0014
PrecSeg(V) x cDur	-0.1534	0.0896	-0.5957	0.8069	0.809	0.642
FollSeg(imp) x cTime	0.0083	0.0109	0.0009	0.0223	0.0488	0.0848
FollSeg(none) x cTime	-0.0098	-0.0134	-0.0234	-0.0033	0.0102	0.032

Table 28 continued

	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	Pr(>|t|)
FollSeg(vce) x cTime	-0.0042	-0.0024	-0.0091	0.004	0.4548	0.1527
FollSeg(-vce) x cTime	-0.0034	-0.0029	-0.0088	0.0031	0.345	0.208
FollSeg(V) x cTime	0.045	0.069	0.0129	0.1238	0.015	0.072
cDur x FollSeg(imp)	0.0003	0.0041	-0.0691	0.086	0.9146	0.9923
cDur x FollSeg(none)	0.2212	0.254	0.1834	0.3217	0.0001	0
cDur x FollSeg(vce)	-0.0162	-0.0082	-0.0475	0.0294	0.665	0.3513
cDur x FollSeg(-vce)	0.0033	0.0115	-0.0234	0.0475	0.5254	0.8372
cDur x FollSeg(V)	-0.0996	-0.0279	-0.2995	0.2315	0.8382	0.3884
cDur x cTime	0.0001	0.0001	0	0.0002	0.0144	0.0189
cTime x FollTone(F)	0	0.0012	-0.0056	0.008	0.7228	0.9916
cTime x FollTone(H)	-0.0006	0.0052	-0.001	0.0113	0.1056	0.8162
cTime x FollTone(none)	0.0081	0.0114	0.0019	0.0205	0.0164	0.0484
FollTone(F) x Tone(F)	-2.8537	-2.9442	-6.8954	1.0804	0.1552	0.109
FollTone(H) x Tone(F)	-2.5905	-1.418	-4.9145	1.8272	0.4166	0.0803
FollTone(none) x Tone(F)	-4.0298	-3.5665	-9.2805	2.0205	0.2148	0.1006
FollTone(F) x Tone(H)	-3.1584	-4.7129	-8.3947	-1.1215	0.0122	0.0541
FollTone(H) x Tone(H)	-5.0708	-5.0907	-8.1088	-1.9471	0.0012	0.0003
FollTone(none) x Tone(H)	-2.4599	-1.4823	-6.6744	3.6366	0.5702	0.2867
Tone(F) x PrecTone(F)	-0.8986	0.2729	-3.6954	4.6075	0.9036	0.627
Tone(H) x PrecTone(F)	1.2997	2.886	-0.7102	6.4321	0.1126	0.418
Tone(F) x PrecTone(H)	0.6301	-0.9043	-4.7944	2.7011	0.629	0.7098

Table 28 continued

	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	Pr(>|t|)
Tone(H) x PrecTone(H)	-2.1316	-1.9807	-5.312	1.2528	0.2404	0.1614
Tone(F) x PrecTone(none)	-8.5398	-7.6146	-12.2125	-3.1385	0.0008	0
Tone(H) x PrecTone(none)	-10.2138	-8.2037	-12.2381	-4.5397	0.0001	0
cTime x Tone(F)	-0.015	-0.0139	-0.0217	-0.0062	0.0008	0
cTime x Tone(H)	-0.0126	-0.0089	-0.0157	-0.0027	0.0066	0
cTime x PrecTone(F)	-0.006	-0.0099	-0.0174	-0.0026	0.0072	0.0745
cTime x PrecTone(H)	-0.0064	-0.0059	-0.0113	-0.0002	0.0376	0.0164
cTime x PrecTone(none)	0.0182	0.0721	-0.0228	0.1692	0.1456	0.6768
PrecSeg(imp) x Tone(F)	123.0205	124.7204	99.7854	152.3276	0.0032	0
PrecSeg(none) x Tone(F)	-0.9087	0.339	-3.6265	4.2294	0.8614	0.6217
PrecSeg(vce) x Tone(F)	5.5866	10.6897	-14.6142	36.867	0.4186	0.629
PrecSeg(-vce) x Tone(F)	-0.755	-1.0794	-3.3627	1.1616	0.3468	0.4636
PrecSeg(V) x Tone(F)	2.9056	1.36	-1.7397	4.798	0.4238	0.0567
PrecSeg(imp) x Tone(H)	10.9602	6.8855	-14.6093	30.2496	0.5438	0.2821
PrecSeg(none) x Tone(H)	-0.0234	-0.0355	-0.0656	-0.0041	0.0222	0.0969
PrecSeg(vce) x Tone(H)	0.6324	2.8364	-0.0287	5.7804	0.0552	0.6238
PrecSeg(-vce) x Tone(H)	2.0319	4.329	0.7753	8.173	0.02	0.2369
PrecSeg(V) x Tone(H)	-0.76	0.237	-1.407	2.0227	0.7784	0.3329
PrecSeg(imp) x Tone(F)	-2.3496	-2.5868	-3.9096	-1.213	0.0004	0.0002

Table 29. Coefficients for Serial Model

	Estimate	**Std. Error**	**|t|**
(Intercept)	136.60000	6.73400	20.288
Tone(H)	0.41790	0.59640	0.701
Tone(L)	-11.91000	0.63870	18.643
Tone(unspecified)	-5.74700	1.75900	3.268
PrecSegment(none)	-0.78770	1.61800	0.487
PrecSegment(sonorant)	2.78700	0.62270	4.476
PrecSegment(voiced)	1.99600	0.65250	3.059
PrecSegment(voiceless)	8.79700	0.63690	13.814
PrecSegment(vowel)	1.51700	0.83200	1.824
cTime	0.00138	0.00325	0.425
cDur	0.00410	0.00839	0.488
SyllType(open)	-2.13400	0.24670	8.65
RelTime	-0.16740	0.01499	11.17
InverseRT	1.20100	1.48200	0.81
Edge(yes)	-6.55700	0.53610	12.231
Span(same)	12.45000	1.03400	12.034
FollSpan(same)	4.98800	0.98090	5.085
FollSegment(none)	2.32800	0.83170	2.799
FollSegment(sonorant)	2.37000	0.63980	3.705
FollSegment(voiced)	3.95200	0.66780	5.918
FollSegment(voiceless)	0.49460	0.68590	0.721
FollSegment(vowel)	-2.20500	1.49100	1.479
PrecSegment(none) x cTime	-0.00643	0.00347	1.856
PrecSegment(sonorant) x cTime	-0.00575	0.00175	3.283
PrecSegment(voiced) x cTime	-0.01055	0.00176	5.997
PrecSegment(voiceless) x cTime	-0.01461	0.00188	7.765
PrecSegment(vowel) x cTime	-0.01544	0.00214	7.214
cDur x SyllType(open)	-0.03943	0.00556	7.099
cDur x RelTime	0.00162	0.00015	10.922
Tone(H) x cDur	-0.02975	0.00766	3.886
Tone(L) x cDur	0.03126	0.00914	3.421
Tone(unspecified) x cDur	-0.02573	0.01256	2.048
Tone(H) x RelTime	0.14370	0.01307	10.994
Tone(L) x RelTime	0.13410	0.01432	9.365
Tone(unspecified) x RelTime	0.22540	0.02289	9.849
cDur x InverseRT	-0.01466	0.00661	2.217

Table 29 continued

	Estimate	Std. Error	|t|
InverseRT x Edge(yes)	1.11300	0.50050	2.224
Tone(H) x Edge(yes)	0.32590	0.56480	0.577
Tone(L) x Edge(yes)	4.90300	0.61160	8.016
Tone(unspecified) x Edge(yes)	4.49900	0.89310	5.037
cTime x Edge(yes)	0.00342	0.00092	3.733
Tone(H) x cTime	-0.00153	0.00131	1.168
Tone(L) x cTime	0.00324	0.00135	2.4
Tone(unspecified) x cTime	0.00828	0.00260	3.179
cTime x Span(same)	-0.00259	0.00175	1.485
Tone(H) x Span(same)	-6.79500	0.62600	10.854
Tone(L) x Span(same)	-14.61000	0.71920	20.31
Tone(unspecified) x Span(same)	-6.67300	5.01200	1.332
Tone(H) x FollSpan(same)	-2.31400	0.67530	3.426
Tone(L) x FollSpan(same)	2.99000	0.81230	3.681
Tone(unspecified) x FollSpan(same)	-6.70400	13.49000	0.497
RelTime x FollSpan(same)	0.04206	0.01239	3.395
Tone(H) x InverseRT	-1.25300	0.73160	1.713
Tone(L) x InverseRT	-0.29740	0.82910	0.359
Tone(unspecified) x InverseRT	4.29100	1.51000	2.842
cTime x FollSpan(same)	-0.00259	0.00189	1.369
RelTime x Span(same)	-0.11220	0.01198	9.365
InverseRT x Span(same)	1.57300	0.60320	2.608
Span(same) x FollSegment(none)	-5.78300	1.07900	5.358
Span(same) x FollSegment(sonorant)	-2.38300	0.94680	2.516
Span(same) x FollSegment(voiced)	-1.13200	0.98970	1.144
Span(same) x FollSegment(voiceless)	-0.15150	0.96340	0.157
Span(same) x FollSegment(vowel)	-7.30800	1.63400	4.473
FollSpan(same) x FollSegment(none)	-0.53320	2.71900	0.196
FollSpan(same) x FollSegment(sonorant)	-4.16700	0.87550	4.76
FollSpan(same) x FollSegment(voiced)	-10.49000	0.97470	10.763
FollSpan(same) x FollSegment(voiceless)	-3.57100	0.90970	3.925
FollSpan(same) x FollSegment(vowel)	5.79600	1.83500	3.159
InverseRT x FollSegment(none)	5.34900	1.12600	4.749
InverseRT x FollSegment(sonorant)	3.14100	0.99970	3.142
InverseRT x FollSegment(voiced)	3.76000	1.05400	3.567
InverseRT x FollSegment(voiceless)	4.07500	1.02700	3.969

Table 29 continued

	Estimate	Std. Error	|t|
InverseRT x FollSegment(vowel)	0.66910	1.25600	0.533
cTime x FollSegment(none)	-0.01281	0.00243	5.282
cTime x FollSegment(sonorant)	-0.00741	0.00204	3.636
cTime x FollSegment(voiced)	-0.00999	0.00210	4.761
cTime x FollSegment(voiceless)	-0.01620	0.00219	7.403
cTime x FollSegment(vowel)	0.00059	0.00296	0.201
PrecSegment(none) x RelTime	-0.03245	0.02465	1.317
PrecSegment(sonorant) x RelTime	0.01192	0.01143	1.043
PrecSegment(voiced) x RelTime	0.01225	0.01220	1.004
PrecSegment(voiceless) x RelTime	-0.04462	0.01177	3.792
PrecSegment(vowel) x RelTime	-0.00951	0.01433	0.663
PrecSegment(none) x InverseRT	5.90100	2.02700	2.911
PrecSegment(sonorant) x InverseRT	-6.22300	1.09600	5.68
PrecSegment(voiced) x InverseRT	-6.83200	1.14300	5.977
PrecSegment(voiceless) x InverseRT	1.87400	1.12300	1.669
PrecSegment(vowel) x InverseRT	-6.05700	1.28100	4.729
Tone(H) x cDur x RelTime	-0.00101	0.00017	5.832
Tone(L) x cDur x RelTime	-0.00165	0.00021	7.759
Tone(unspecified) x cDur x RelTime	-0.00153	0.00024	6.489
Tone(H) x cTime x Span(same)	-0.00390	0.00197	1.984
Tone(L) x cTime x Span(same)	-0.00812	0.00225	3.608
Tone(unspecified) x cTime x Span(same)	-0.00910	0.01873	0.486
Tone(H) x RelTime x FollSpan(same)	-0.03261	0.01452	2.247
Tone(L) x RelTime x FollSpan(same)	-0.05811	0.01825	3.185
Tone(unspecified) x RelTime x FollSpan(same)	-0.05819	0.09120	0.638
Tone(H) x cTime x FollSpan(same)	0.00739	0.00233	3.173
Tone(L) x cTime x FollSpan(same)	0.00606	0.00225	2.7
Tone(unspecified) x cTime x FollSpan(same)	0.00428	0.05394	0.079
Tone(H) x RelTime x Span(same)	0.08123	0.01380	5.885
Tone(L) x RelTime x Span(same)	0.13690	0.01615	8.48
Tone(unspecified) x RelTime x Span(same)	0.15070	0.11250	1.339

Table 30. MCMC Values for Serial Model

	Estimate	MCMC mean	HPD95 lower	HPD95 upper	p MCMC	Pr(>|t|)
(Intercept)	136.6077	136.5454	109.4021	164.0419	0.0026	0
Tone(H)	0.4179	0.4172	-0.7704	1.5681	0.4772	0.4836
Tone(L)	-11.9083	-11.9048	-13.1427	-10.611	0.0001	0
Tone(unspec)	-5.7472	-5.777	-9.2974	-2.4135	0.0012	0.0011
PrecSeg(none)	-0.7877	-0.7539	-3.8863	2.4769	0.6478	0.6263
PrecSeg(son)	2.7873	2.7919	1.5802	3.9895	0.0001	0
PrecSeg(vce)	1.9962	2.004	0.7312	3.2808	0.0012	0.0022
PrecSeg(-vce)	8.7974	8.802	7.5206	10.0208	0.0001	0
PrecSeg(V)	1.5174	1.5293	-0.058	3.1681	0.0624	0.0682
cTime	0.0014	0.0014	-0.0045	0.008	0.6718	0.6707
cDur	0.0041	0.004	-0.0114	0.0215	0.6358	0.6256
SyllType(open)	-2.1339	-2.1347	-2.6194	-1.6503	0.0001	0
RelTime	-0.1674	-0.1675	-0.1975	-0.1376	0.0001	0
InverseRT	1.2007	1.2043	-1.6251	4.1962	0.404	0.4179
Edge(yes)	-6.5571	-6.5643	-7.6491	-5.5502	0.0001	0
Span(same)	12.4469	12.4562	10.4981	14.5014	0.0001	0
FollSpan(same)	4.9884	4.9989	3.117	6.9637	0.0001	0
FollSeg(none)	2.3281	2.3299	0.7591	4.0019	0.005	0.0051
FollSeg(son)	2.37	2.3668	1.0641	3.5953	0.0001	0.0002
FollSeg(vce)	3.9518	3.9458	2.6519	5.2313	0.0001	0
FollSeg(-vce)	0.4946	0.4949	-0.8388	1.8287	0.4728	0.4709
FollSeg(V)	-2.2047	-2.1892	-5.0375	0.7853	0.1514	0.1392
PrecSeg(none) x cTime	-0.0064	-0.0064	-0.0131	0.0005	0.0658	0.0635
PrecSeg(son) x cTime	-0.0058	-0.0058	-0.0092	-0.0024	0.001	0.001
PrecSeg(vce) x cTime	-0.0106	-0.0106	-0.014	-0.0072	0.0001	0
PrecSeg(-vce) x cTime	-0.0146	-0.0146	-0.0182	-0.0109	0.0001	0
PrecSeg(V) x cTime	-0.0154	-0.0155	-0.0197	-0.0113	0.0001	0
cDur x SyllType(open)	-0.0394	-0.0394	-0.0506	-0.0288	0.0001	0
cDur x RelTime	0.0016	0.0016	0.0013	0.0019	0.0001	0
Tone(H) x cDur	-0.0297	-0.0297	-0.0444	-0.0142	0.0001	0.0001
Tone(L) x cDur	0.0313	0.0313	0.014	0.0502	0.0004	0.0006
Tone(unspec) x cDur	-0.0257	-0.0257	-0.0499	-0.0007	0.0404	0.0405
Tone(H) x RelTime	0.1437	0.1437	0.1172	0.1692	0.0001	0
Tone(L) x RelTime	0.1341	0.134	0.1071	0.1633	0.0001	0
Tone(unspec) x RelTime	0.2254	0.2257	0.1795	0.2699	0.0001	0

Table 30 continued

	Estimate	MCMC mean	HPD95 lower	HPD95 upper	p MCMC	Pr(>|t|)
cDur x InverseRT	-0.0147	-0.0146	-0.0279	-0.0021	0.0274	0.0267
InverseRT x Edge(yes)	1.113	1.1147	0.1482	2.0807	0.0276	0.0262
Tone(H) x Edge(yes)	0.3259	0.334	-0.7546	1.4503	0.5604	0.5639
Tone(L) x Edge(yes)	4.9026	4.9034	3.7298	6.1292	0.0001	0
Tone(unspec) x Edge(yes)	4.4988	4.4994	2.7446	6.2631	0.0001	0
cTime x Edge(yes)	0.0034	0.0034	0.0016	0.0052	0.0004	0.0002
Tone(H) x cTime	-0.0015	-0.0015	-0.0041	0.0011	0.2414	0.2429
Tone(L) x cTime	0.0032	0.0032	0.0006	0.0058	0.0186	0.0164
Tone(unspec) x cTime	0.0083	0.0083	0.0035	0.0136	0.001	0.0015
cTime x Span(same)	-0.0026	-0.0026	-0.0061	0.0008	0.139	0.1377
Tone(H) x Span(same)	-6.7951	-6.8009	-8.0598	-5.5968	0.0001	0
Tone(L) x Span(same)	-14.6071	-14.6082	-16.0267	-13.1596	0.0001	0
Tone(unspec) x Span(same)	-6.6733	-6.6106	-16.4455	3.0576	0.1858	0.183
Tone(H) x FollSpan(same)	-2.3136	-2.315	-3.6537	-1.0269	0.0004	0.0006
Tone(L) x FollSpan(same)	2.9905	2.9934	1.4355	4.5957	0.0006	0.0002
Tone(unspec) x FollSpan(same)	-6.7045	-6.8165	-33.0747	19.8442	0.6124	0.6193
RelTime x FollSpan(same)	0.0421	0.042	0.0177	0.066	0.0006	0.0007
Tone(H) x InverseRT	-1.2529	-1.2537	-2.6747	0.1724	0.086	0.0868
Tone(L) x InverseRT	-0.2974	-0.3043	-2.0322	1.2438	0.722	0.7198
Tone(unspec) x InverseRT	4.2907	4.3211	1.2208	7.1585	0.0056	0.0045
cTime x FollSpan(same)	-0.0026	-0.0026	-0.0062	0.0012	0.1702	0.171
RelTime x Span(same)	-0.1122	-0.1123	-0.1347	-0.0878	0.0001	0
InverseRT x Span(same)	1.5731	1.5743	0.3755	2.74	0.0072	0.0091
Span(same) x FollSeg(none)	-5.783	-5.792	-7.8751	-3.6843	0.0001	0
Span(same) x FollSeg(son)	-2.3825	-2.3866	-4.2659	-0.6025	0.0112	0.0119
Span(same) x FollSeg(vce)	-1.132	-1.1339	-3.0089	0.8403	0.246	0.2527
Span(same) x FollSeg(-vce)	-0.1515	-0.1615	-2.0091	1.7374	0.8668	0.8751
Span(same) x	-7.3082	-7.3368	-10.4301	-4.0588	0.0001	0

Table 30 continued

	Estimate	MCMC mean	HPD95 lower	HPD95 upper	p MCMC	Pr(>|t|)
FollSeg(V)						
FollSpan(same) x FollSeg(none)	-0.5332	-0.526	-5.8919	4.6717	0.8384	0.8446
FollSpan(same) x FollSeg(son)	-4.1673	-4.1724	-5.8446	-2.4489	0.0001	0
FollSpan(same) x FollSeg(vce)	-10.4907	-10.5034	-12.373	-8.5912	0.0001	0
FollSpan(same) x FollSeg(-vce)	-3.5705	-3.5777	-5.3523	-1.823	0.0001	0.0001
FollSpan(same) x FollSeg(V)	5.7962	5.7967	2.2348	9.4516	0.0012	0.0016
InverseRT x FollSeg(none)	5.3486	5.3478	3.1093	7.4868	0.0001	0
InverseRT x FollSeg(son)	3.1414	3.1437	1.1912	5.0475	0.0012	0.0017
InverseRT x FollSeg(vce)	3.7599	3.76	1.6786	5.7013	0.0004	0.0004
InverseRT x FollSeg(-vce)	4.075	4.0755	2.1315	6.0831	0.0001	0.0001
InverseRT x FollSeg(V)	0.6691	0.6621	-1.7988	3.0286	0.5976	0.5943
cTime x FollSeg(none)	-0.0128	-0.0128	-0.0174	-0.008	0.0001	0
cTime x FollSeg(son)	-0.0074	-0.0074	-0.0113	-0.0033	0.0006	0.0003
cTime x FollSeg(vce)	-0.01	-0.01	-0.0142	-0.006	0.0001	0
cTime x FollSeg(-vce)	-0.0162	-0.0162	-0.0205	-0.012	0.0001	0
cTime x FollSeg(V)	0.0006	0.0006	-0.0051	0.0064	0.8384	0.8407
PrecSeg(none) x RelTime	-0.0325	-0.0328	-0.0812	0.0156	0.1826	0.188
PrecSeg(son) x RelTime	0.0119	0.012	-0.0104	0.0342	0.299	0.2971
PrecSeg(vce) x RelTime	0.0123	0.0123	-0.0109	0.0369	0.3086	0.3153
PrecSeg(-vce) x RelTime	-0.0446	-0.0446	-0.0679	-0.0221	0.0001	0.0001
PrecSeg(V) x RelTime	-0.0095	-0.0096	-0.0371	0.0188	0.507	0.5071
PrecSeg(none) x InverseRT	5.9008	5.8756	1.6185	9.5785	0.0028	0.0036
PrecSeg(son) x InverseRT	-6.2231	-6.2274	-8.4024	-4.135	0.0001	0
PrecSeg(vce) x InverseRT	-6.832	-6.8397	-9.0786	-4.6402	0.0001	0
PrecSeg(-vce) x InverseRT	1.8741	1.8774	-0.255	4.0984	0.0948	0.0951

Table 30 continued

	Estimate	MCMC mean	HPD95 lower	HPD95 upper	p MCMC	Pr(>|t|)
PrecSeg(V) x InverseRT	-6.0573	-6.0695	-8.6187	-3.6596	0.0001	0
Tone(H) x cDur x RelTime	-0.001	-0.001	-0.0014	-0.0007	0.0001	0
Tone(L) x cDur x RelTime	-0.0016	-0.0016	-0.0021	-0.0012	0.0001	0
Tone(unspec) x cDur x RelTime	-0.0015	-0.0015	-0.002	-0.001	0.0001	0
Tone(H) x cTime x Span(same)	-0.0039	-0.0039	-0.0078	0	0.0518	0.0473
Tone(L) x cTime x Span(same)	-0.0081	-0.0081	-0.0125	-0.0038	0.0008	0.0003
Tone(unspec) x cTime x Span(same)	-0.0091	-0.009	-0.0453	0.0287	0.6346	0.6272
Tone(H) x RelTime x FollSpan(same)	-0.0326	-0.0326	-0.0602	-0.0042	0.0254	0.0247
Tone(L) x RelTime x FollSpan(same)	-0.0581	-0.0581	-0.0945	-0.0227	0.001	0.0015
Tone(unspec) x RelTime x FollSpan(same)	-0.0582	-0.0577	-0.2403	0.1178	0.5276	0.5235
Tone(H) x cTime x FollSpan(same)	0.0074	0.0074	0.0026	0.0117	0.0016	0.0015
Tone(L) x cTime x FollSpan(same)	0.0061	0.0061	0.0016	0.0105	0.0068	0.0069
Tone(unspec) x cTime x FollSpan(same)	0.0043	0.0038	-0.1005	0.111	0.9498	0.9367
Tone(H) x RelTime x Span(same)	0.0812	0.0814	0.0544	0.1081	0.0001	0
Tone(L) x RelTime x Span(same)	0.1369	0.137	0.1061	0.169	0.0001	0
Tone(unspec) x RelTime x Span(same)	0.1507	0.1496	-0.0722	0.3709	0.1868	0.1805

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